Fire Master Class, University of Tasmania, Australia, Oct 9-11, 2013

Development of Global Fire Scheme in the Earth System Model

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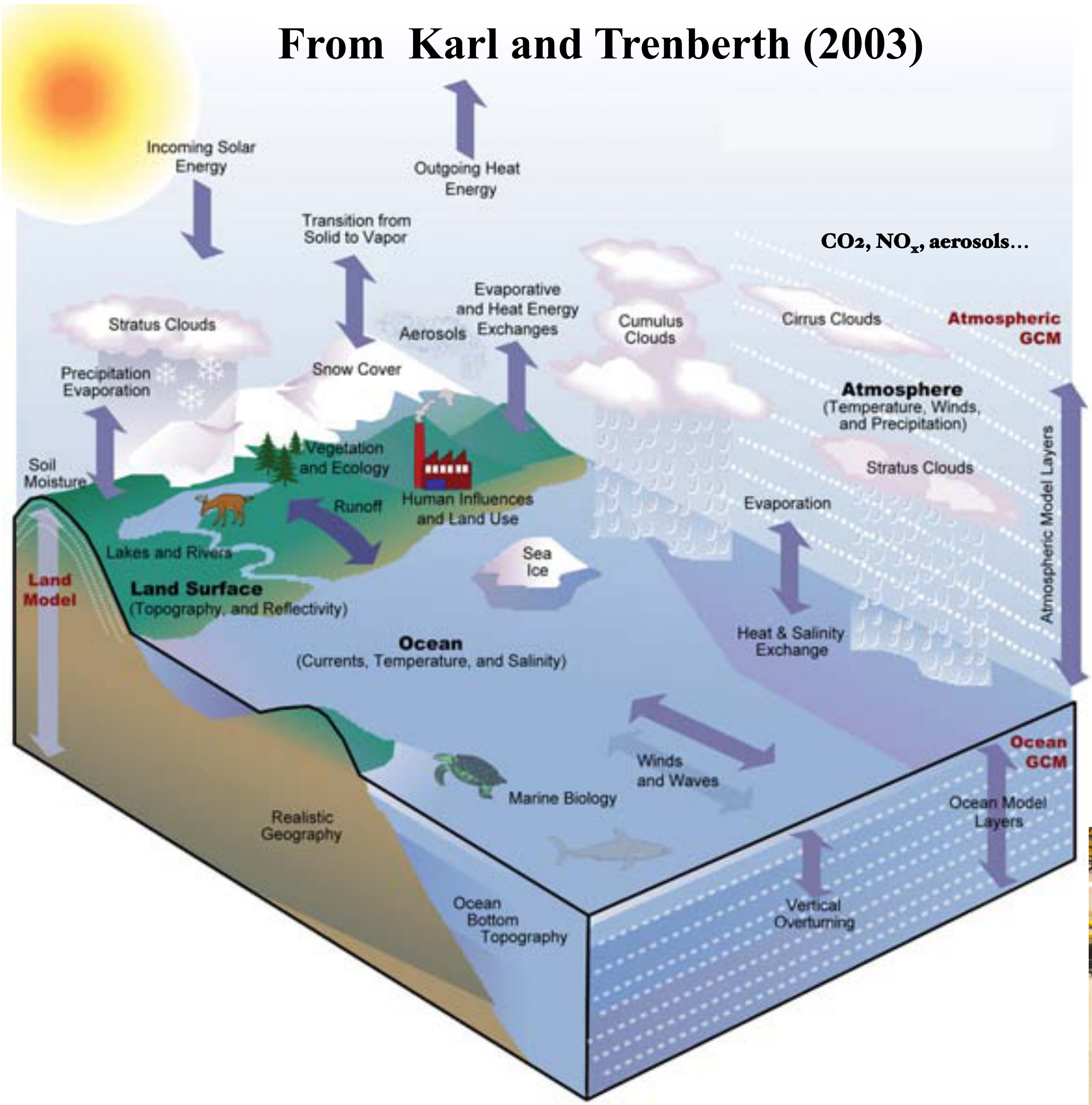
Outline

- **Background**
  - **Earth system model (ESM)**
  - **Land component of ESM: land surface model**
  - **Ecosystem component of land surface model: Biogeochemical model, and Dynamic Global Vegetation Model (DGVM)**
  - **Interactions among fire, vegetation/C , land, and atmosphere**
- **Global fire schemes for ESMs**
  - **Review earlier ones**
  - **Describe our new one**
- **Quantifying the impact of fire on global net eco. C balance during the 20^{th} century**
- **Near future works**
  - **Development of fire scheme**
  - **Application of global fire scheme**

Earth system model (ESM)



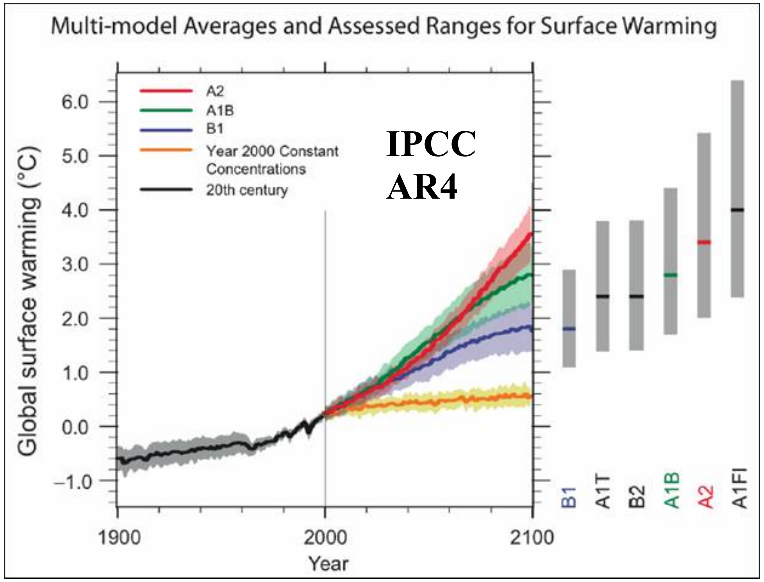
From Karl and Trenberth (2003)

•What are ESM

ESM is (science: a set of equations; tech.: a heap of code) describing processes within and between the Atmosphere (phy. and chem.), ocean, land, cryosphere (sea and land ice, snow…), and biosphere (terrestrial and marine)

From: http://www2.cisl.ucar.edu/resources/yellowstone

- **Why do we need ESMs**

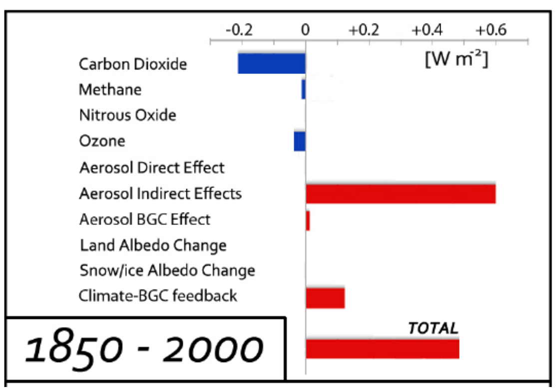


1. Reconstruct the past and project the future

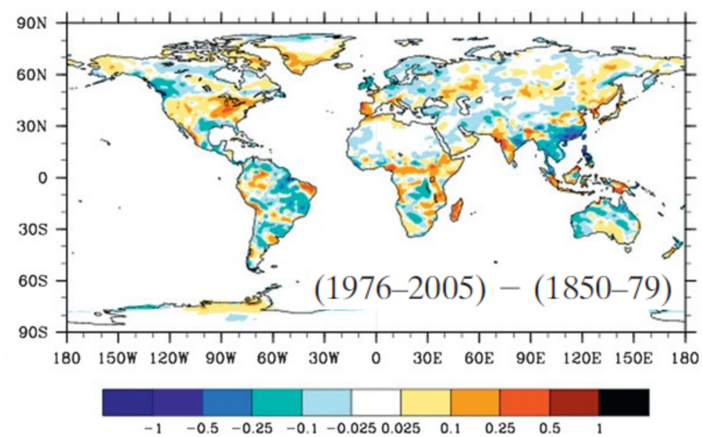
Advantages.:

Interactions included, physically consistent

2. Understand the Earth system



Impact of fire emis. on rad. forcing (Ward et al. 2012)



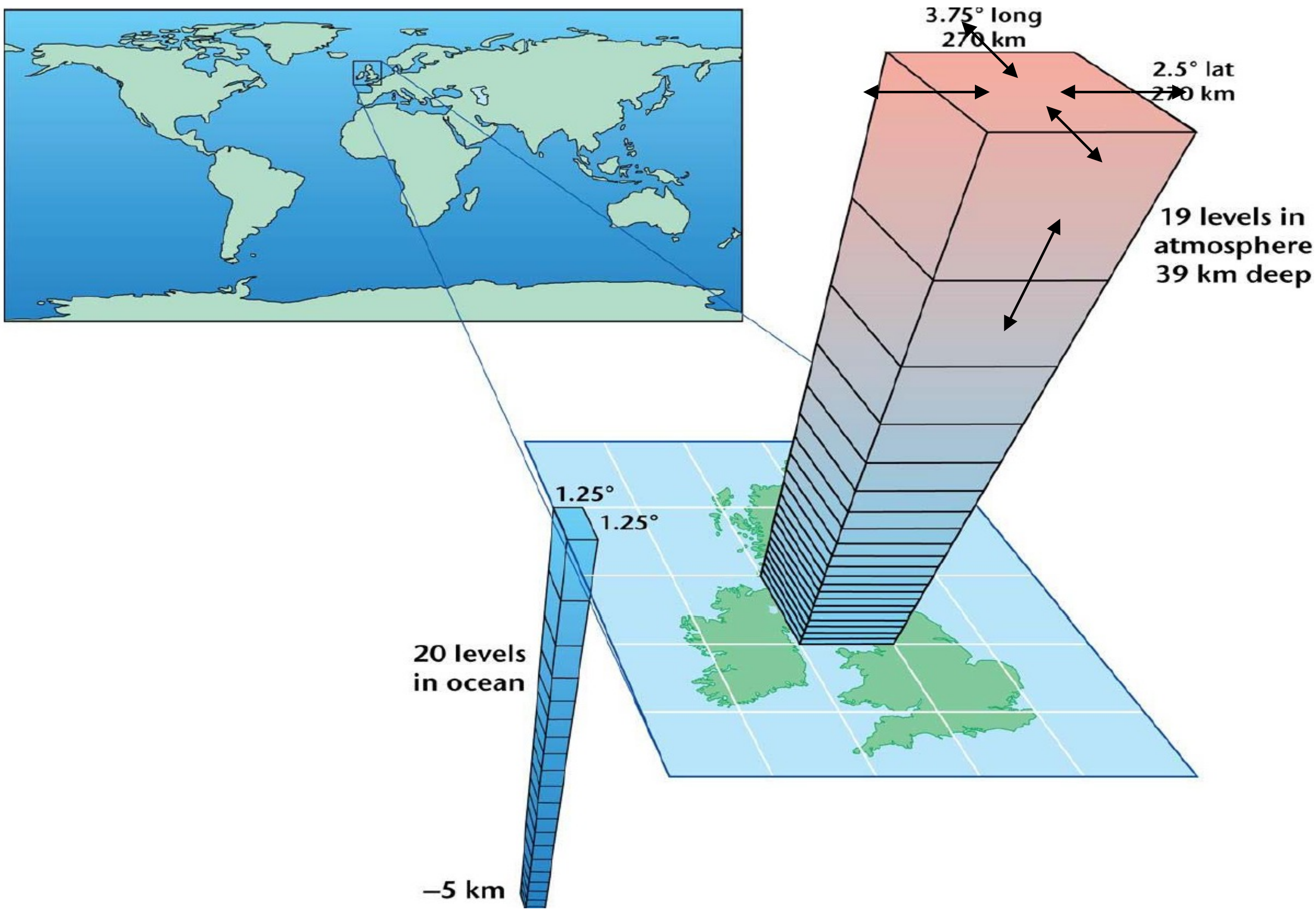
Impact of land use and cover change on precip. (Lawrence et al. 2012)

•Schematic for recent ESMs

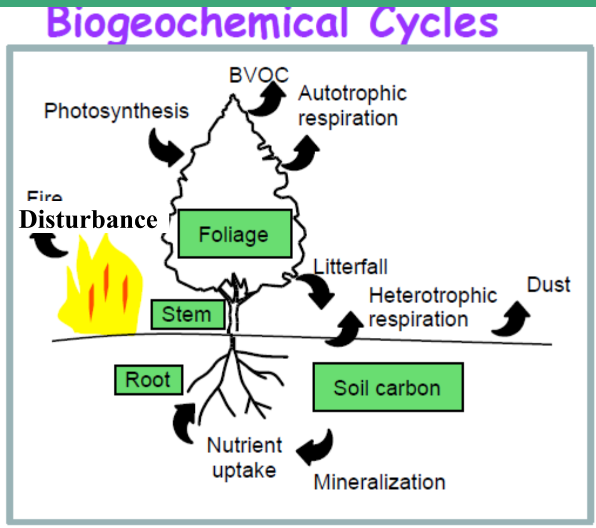
Atm. and Ocean components: three dimensional grid

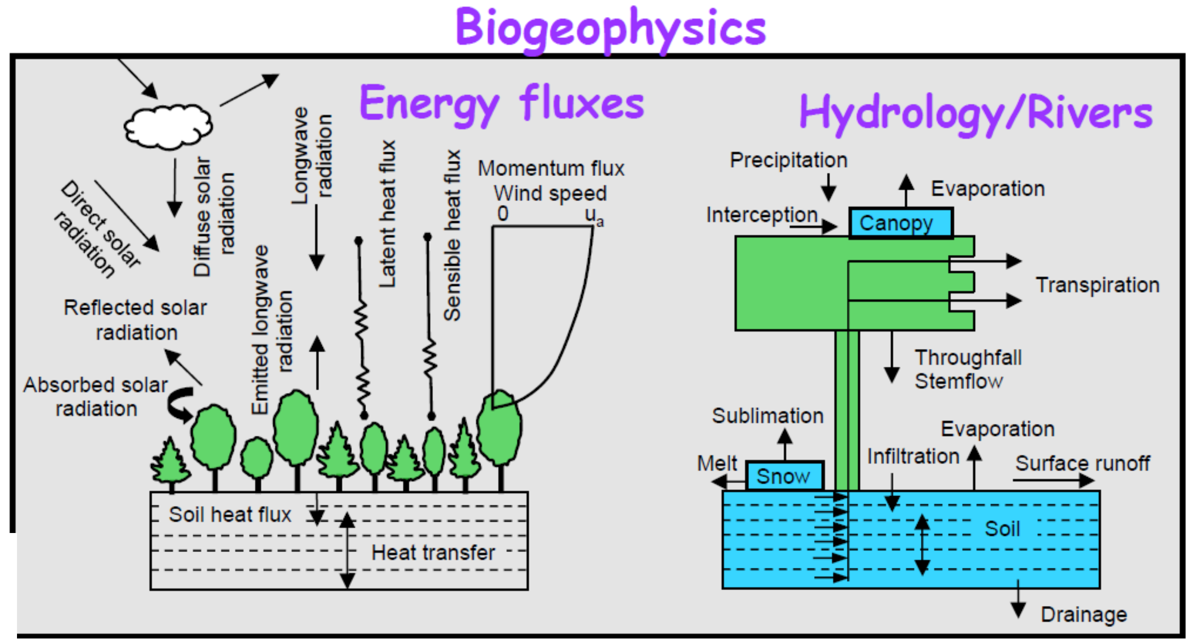
Land component: one dimension grid (vertical)

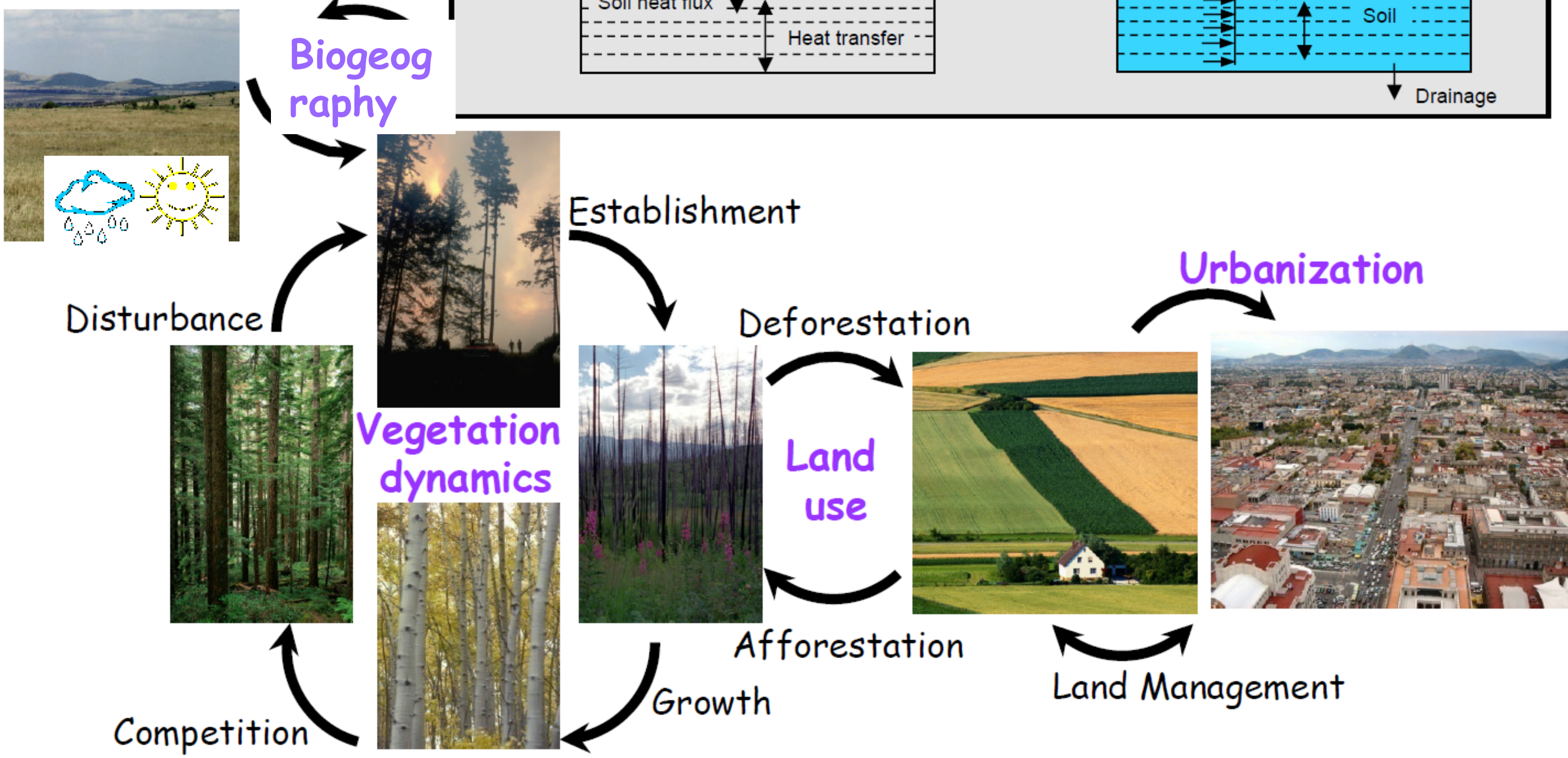
•Res.: ~10^4 km^2 (horizontal), 10^1 layer (vertical), sub-hourly −1 year (temporal)



Land component of ESM: Land surface model



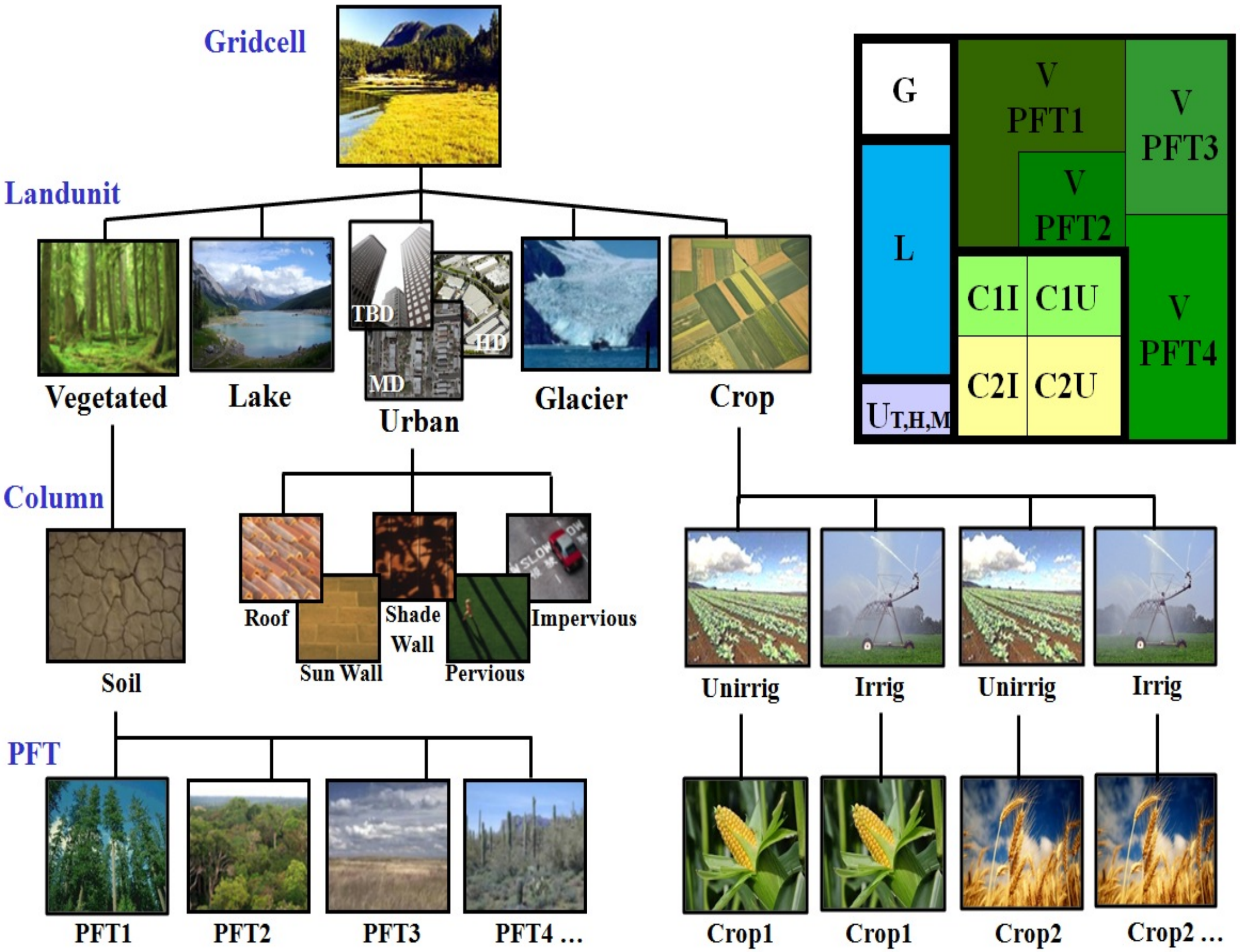




NCAR CLM4, CLM4.5

(Levis, 2013)

Describe the spatial heterogeneity of land surface



Natural Plant Functional types (PFTs) used in NCAR CLM4.5

Trees

Needleleaf evergreen tree-temperate
Needleleaf evergreen tree-boreal
Needleleaf deciduous tree-boreal
Broadleaf evergreen tree-tropical
Broadleaf evergreen tree-temperate
Broadleaf deciduous tree-tropical
Broadleaf deciduous tree-temperate
Broadleaf deciduous tree-boreal

Shrub

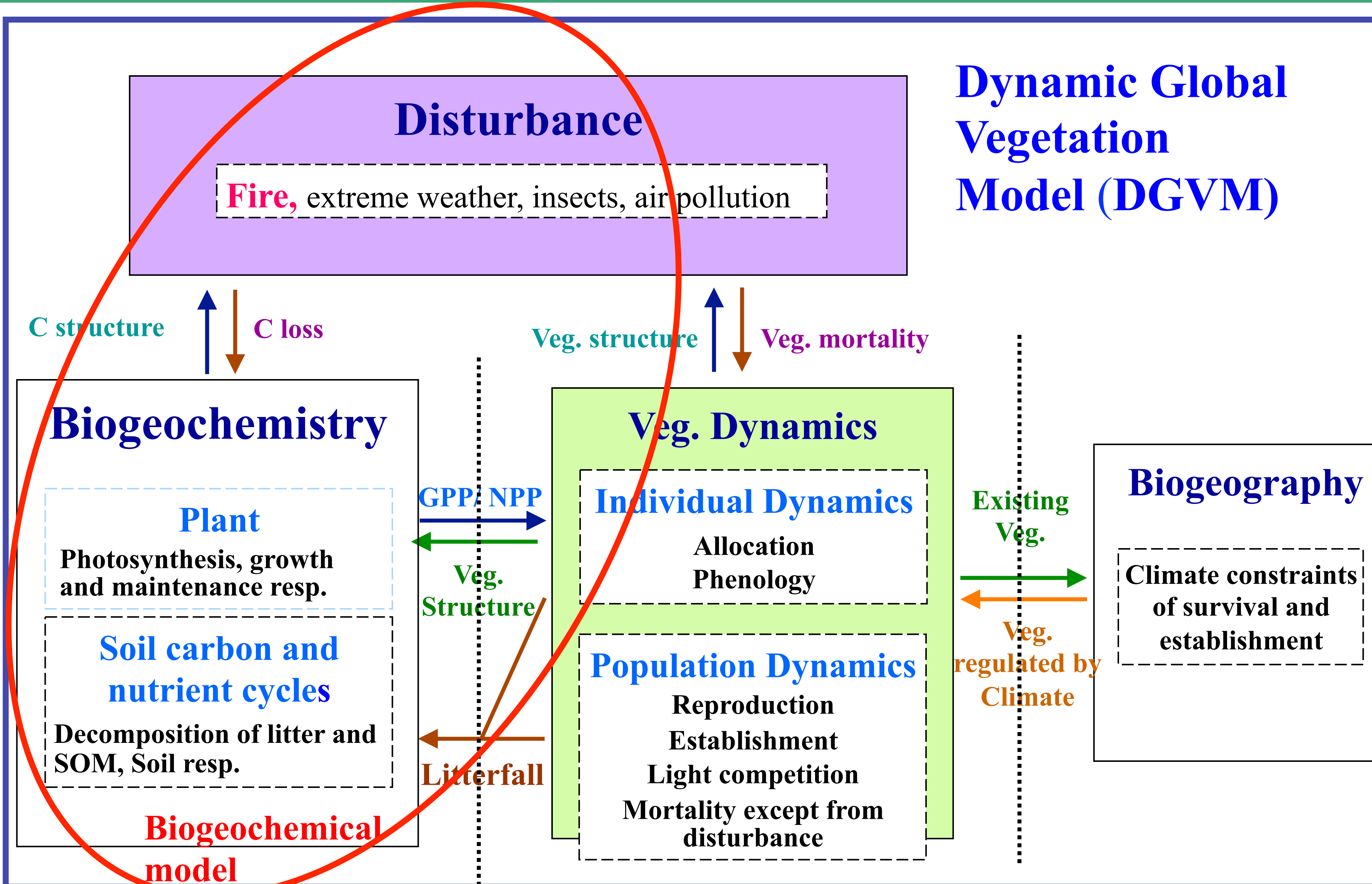
Broadleaf evergreen tree-temperate
Broadleaf deciduous tree-temperate
Broadleaf deciduous tree-boreal

Grass

C3 arctic grass
C3 grass
C4 grass

CLM4.5 (Keith et al., 2013)

Ecosystem component of land surface model



•Interactions among fire, vegetation/C/N , land and atmosphere

•Determinants of fire

•Land

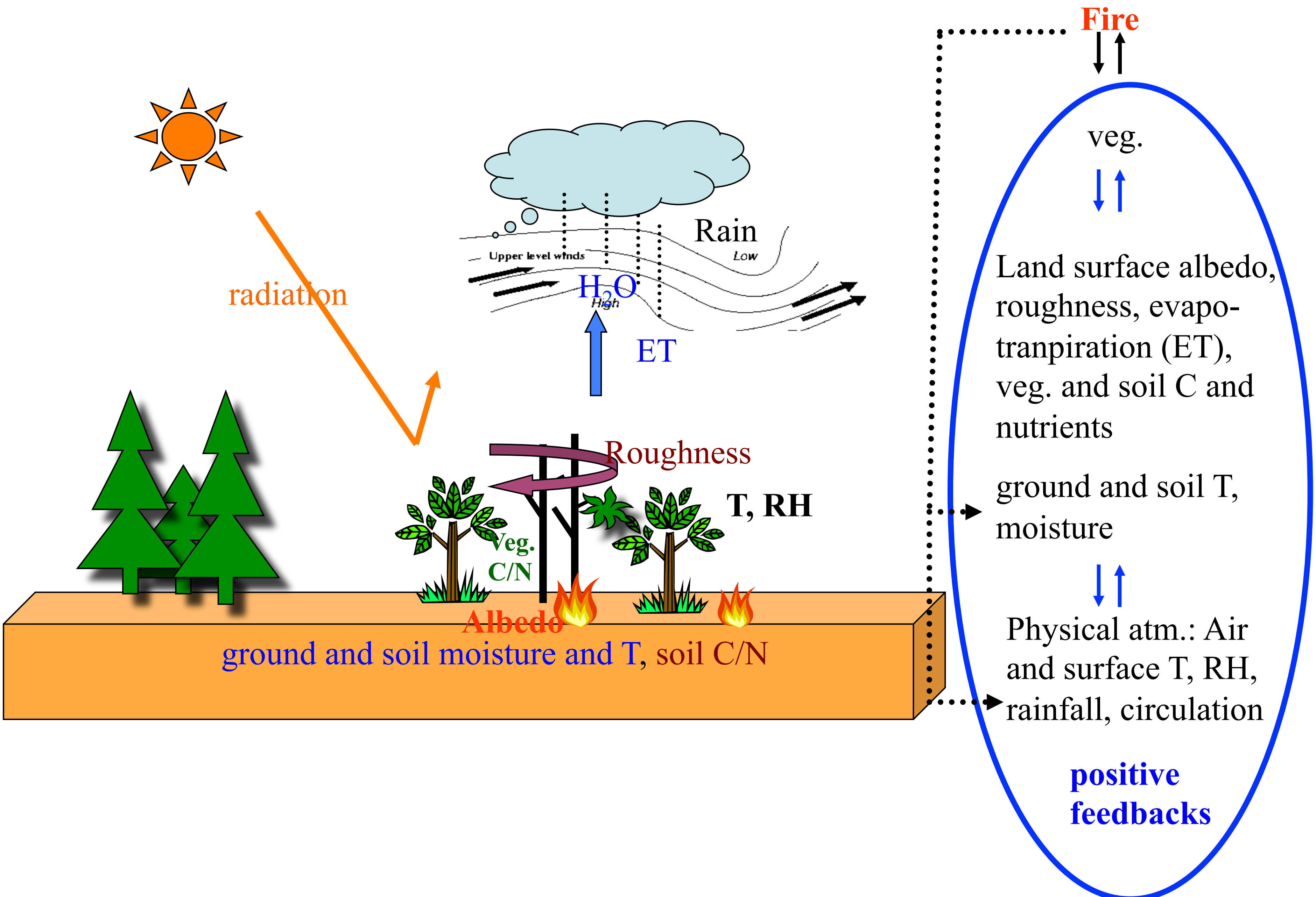
vegetation, C/N cycles,
hydrology….

•Atmosphere
Lightning, P, RH, T, wind …

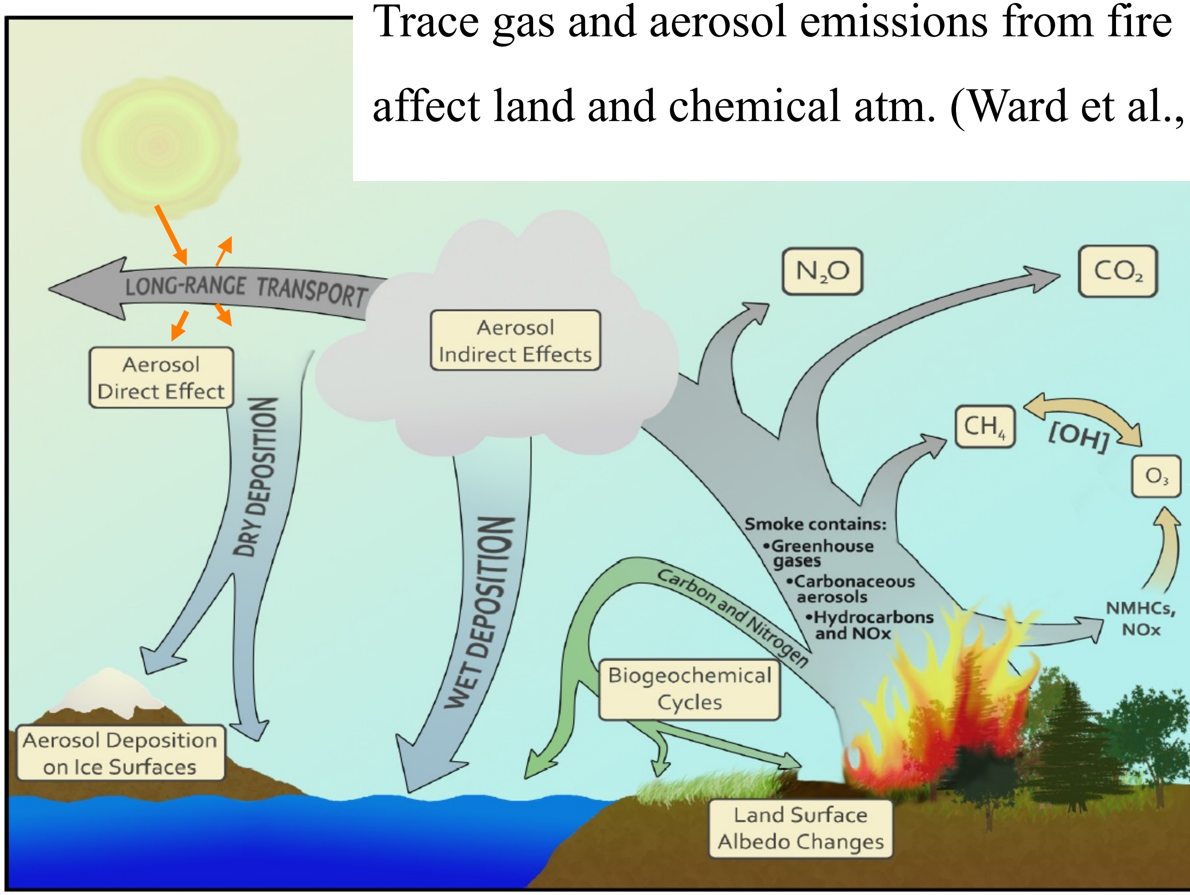
•People

ignition and supression

•Feedbacks of fire



Trace gas and aerosol emissions from fire affect land and chemical atm. (Ward et al., 2013)



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Earlier global fire schemes: three types

1. Simple fire scheme

- **TRIFFID-DGVM: Constant fire loss rate**

- **IBIS-DGVM, ED-DGVM, VEGAS-DGVM, SDGVM:**

  Burn rate=*f* (litter wetness and/or litter amount)

2. Intermediate-complexity and process-based

- **LPJ, CLM4-C/CN/BGC, CLM-DGVM, SEIB-DGVM, ORCHIDEE, ORCHIDEE-C: Glob-FIRM** (Thonicke et al. 2001) **and its modified versions**

- **CTEM-DGVM, an unreleased version of CLM4-CN: CTEM-FIRE** (Arora and Boer, 2005) **and its modified version** (Kloster et al. 2010)

describe the process of fire occurrence, fire spread, and fire impact, but the modeling of each process is statistical/experiential and simple

3. Complex process-based (e.g. SPITFIRE [Thonicke et al. 2010])

- **Processes**

Fire occurrence

Fire spread (Rothermel's equations)

Fire impact

- **Fuel type**

1-h: leaves and twigs (4.5%×stem C)

10-h: small branch (7.5%×stem C)

100-h: large branches (21%×stem C)

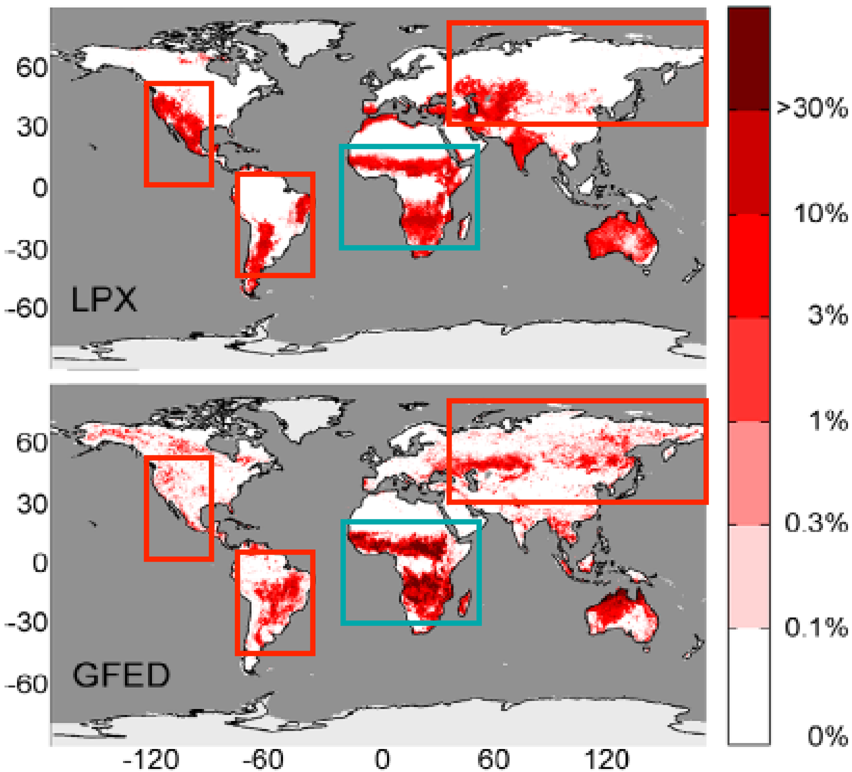
1000-h: boles or trunks (67% %×stem C)

- **Post-fire vegetation mortality:**

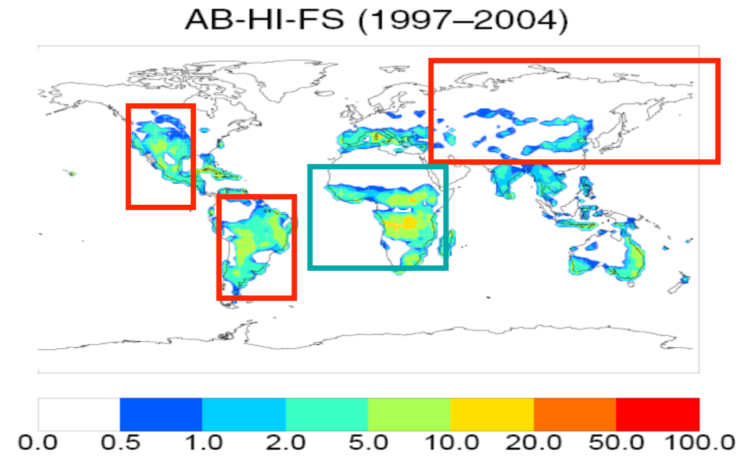
crown damage

cambial damage

1997-2005 average annual fractional burnt area from improved LPJ-SPITFIRE (LPX) and GFED3 (Prentice et al. 2011)



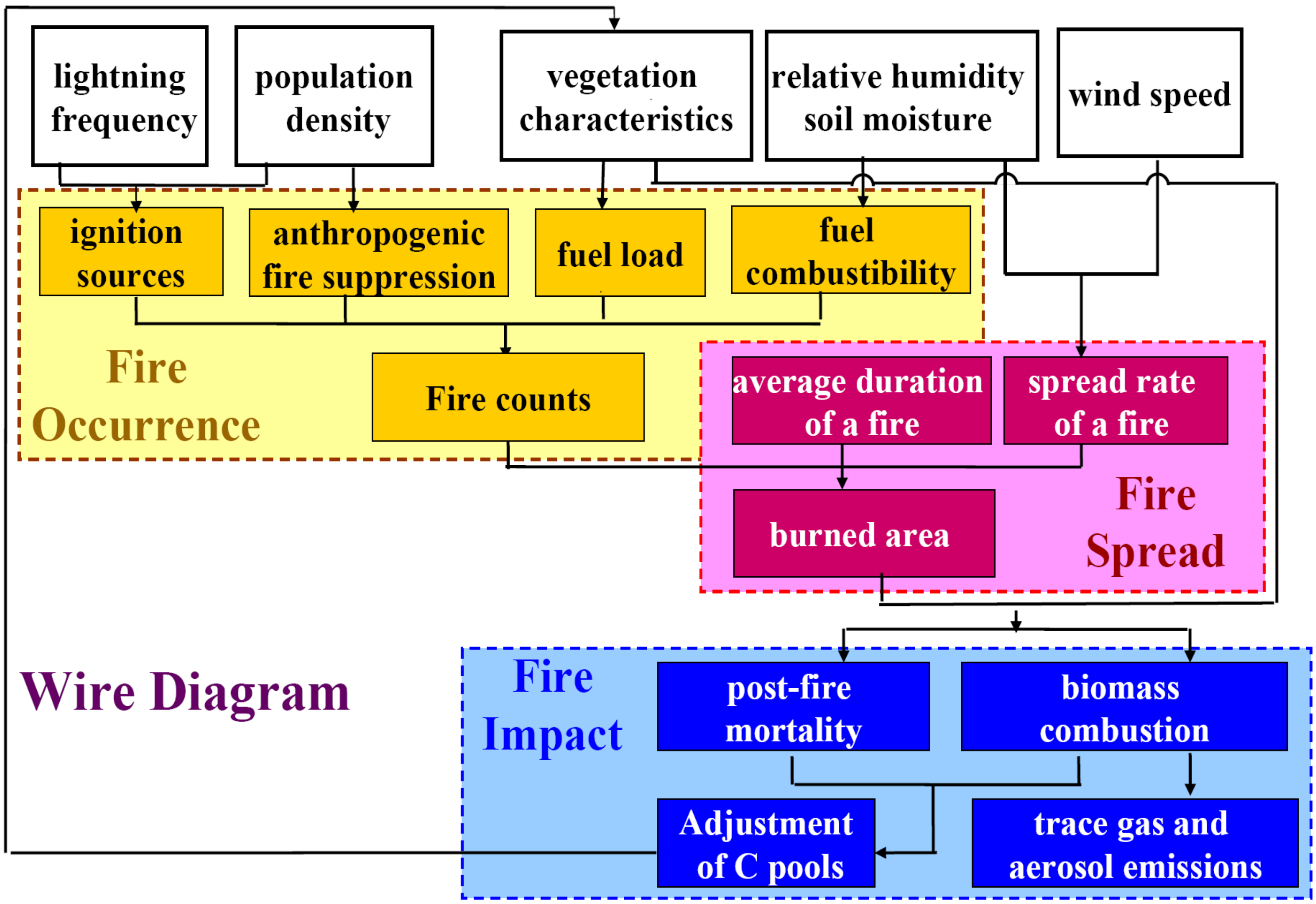
Revised CTEM-FIRE in CLM4-CN (Kloster et al. 2010)



on a global scale, SPITFIRE hasn't shown the benefit of it's complex design

Our global fire schemes

Global fire scheme for IAP-DGVM (Li et al. 2012a,b)



• Fire occurrence

Fire counts in a grid cell (N_f, count/time-step):

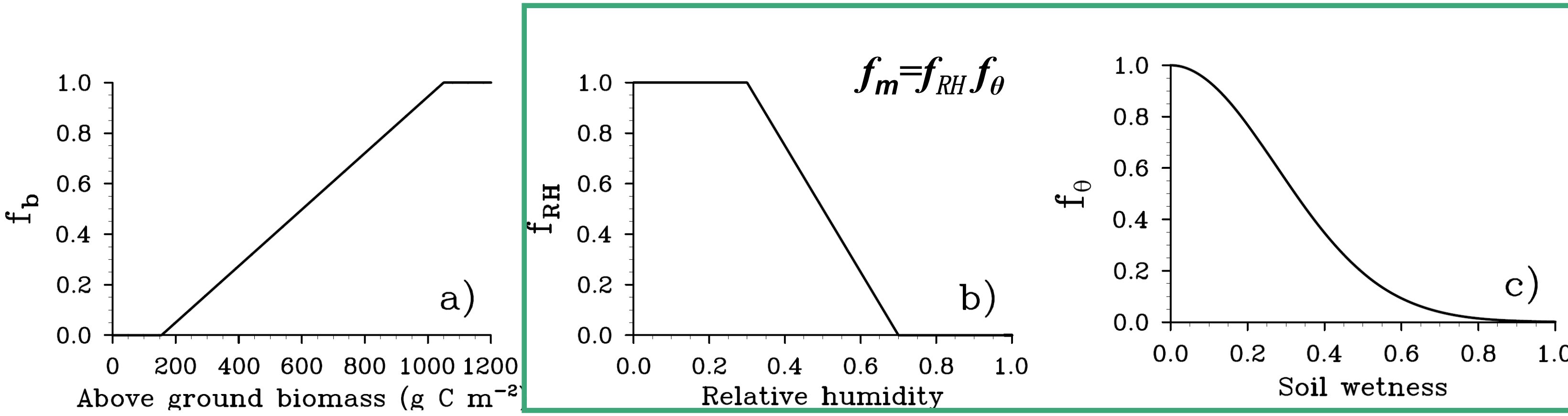
$$N_f = N_i f_b f_m (1 - f_s)$$

Fuel availability (f_b)

Fire suppression rate (f_s)

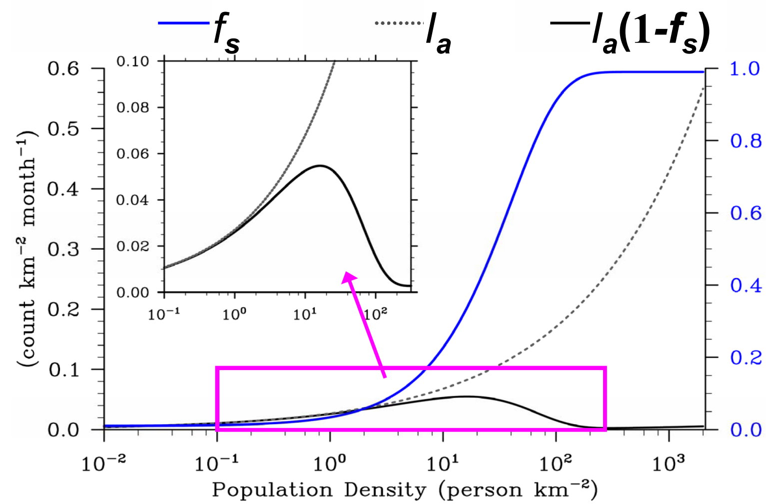
Ignition counts (N_i)

Fuel combustibility (f_m)

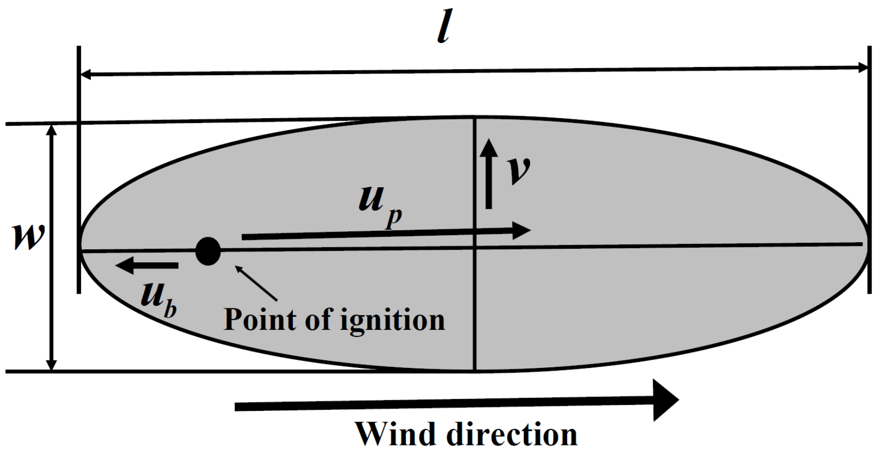


Ignition counts: $N_i = (I_n + I_a)A_g$

- **Ignitions due to lightning** (I_n)
- **human ignition freq.** (I_a)
- **grid-cell area** (A_g)



• Fire spread

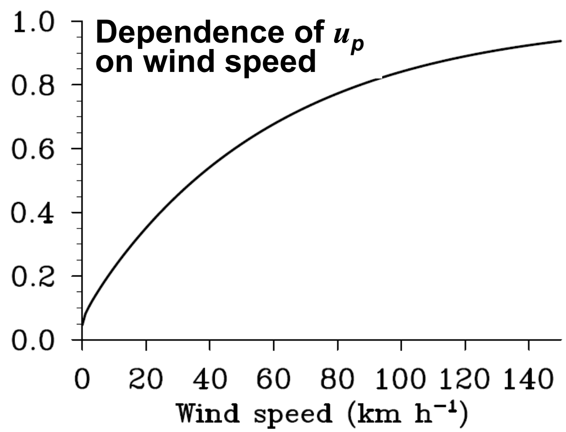


According to the area formula for an ellipse, average burned area of a fire with average fire duration τ(s) can be represented as:

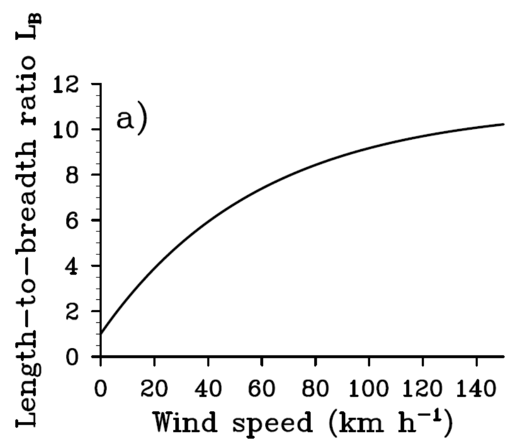
$$a = \pi \frac{l}{2}\frac{w}{2} \times 10^{-6} = \frac{\pi u_p^2 \tau^2}{4L_B}(1 + \frac{1}{H_B})^2 \times 10^{-6}$$

Fire spread rate in the downwind direction:

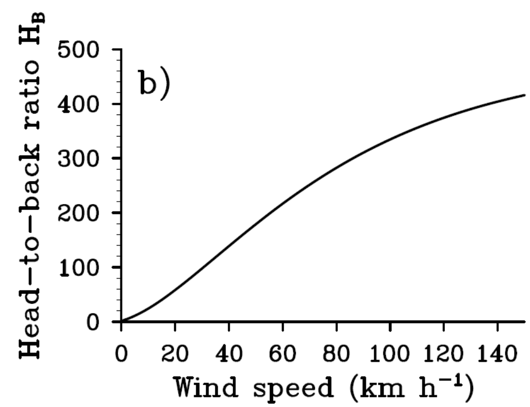
$u_p = f$ **(fuel wetness, wind speed)**



Based on mathematical derivation, functions of L_B and H_B



based on CTEM



According to L_B and mathematical properties of ellipse

Fire impact (PFT-level)

Biomass burning

fire carbon emis.= C pools ×PFT-dependent combustion completeness factor ×burned area frac.

Fire-induced veg. mortality

whole-plant mortality= Pop. den. ×PFT-dependent individual mortality factor 1×burned area frac.

Veg. tissue mortality= C pools ×PFT-dependent tissue mortality factor 2 ×burned area frac.

Fire-induced trace gas and aerosol emissions

=fire C emis. ×PFT-dependent emissions factors

Adjustment of C pool

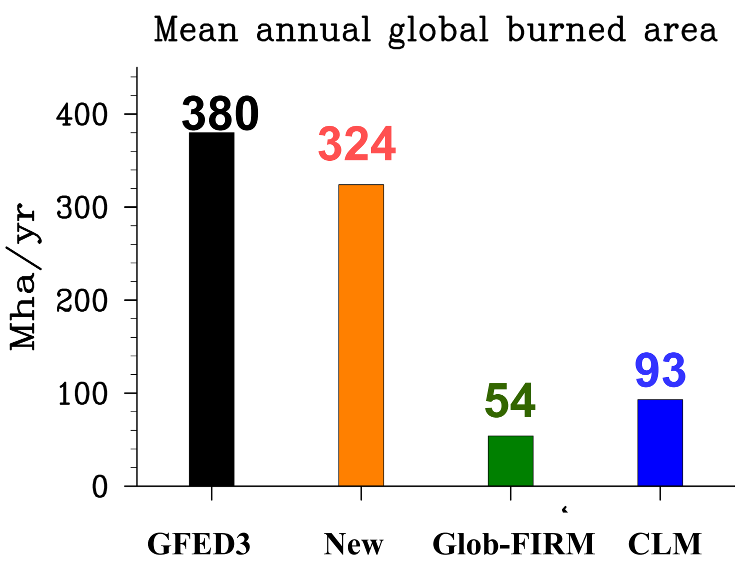
Adjusted C pools for live veg. tissue= Original C pool — C loss due to biomass burning and mortality

Adjusted litter and CWD pools =original C pools — fire carbon emissions + C loss from fire-induced mortality

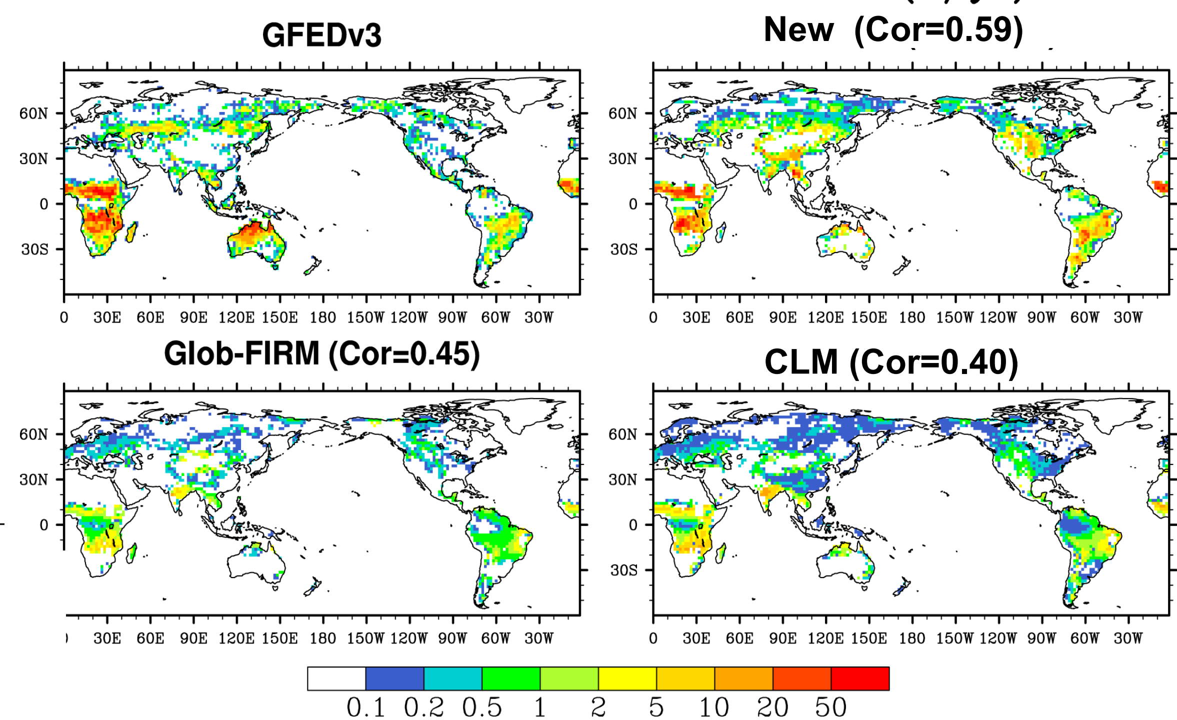
• Results (1997-2004): Burned area

New: Our fire scheme (Li et al. 2012a,b)
Glob-FIRM: most commonly-used global fire scheme (Thonicke et al. 2001)
CLM: modified Glob-FIRM (Levis et al. 2004)
All fire schemes are tested in the same model-platform, 1970-2004 equilibrium simulation, common period between obs. and sim. is 1997-2004

•Cor: global spatial correlation between Obs. and Sims.

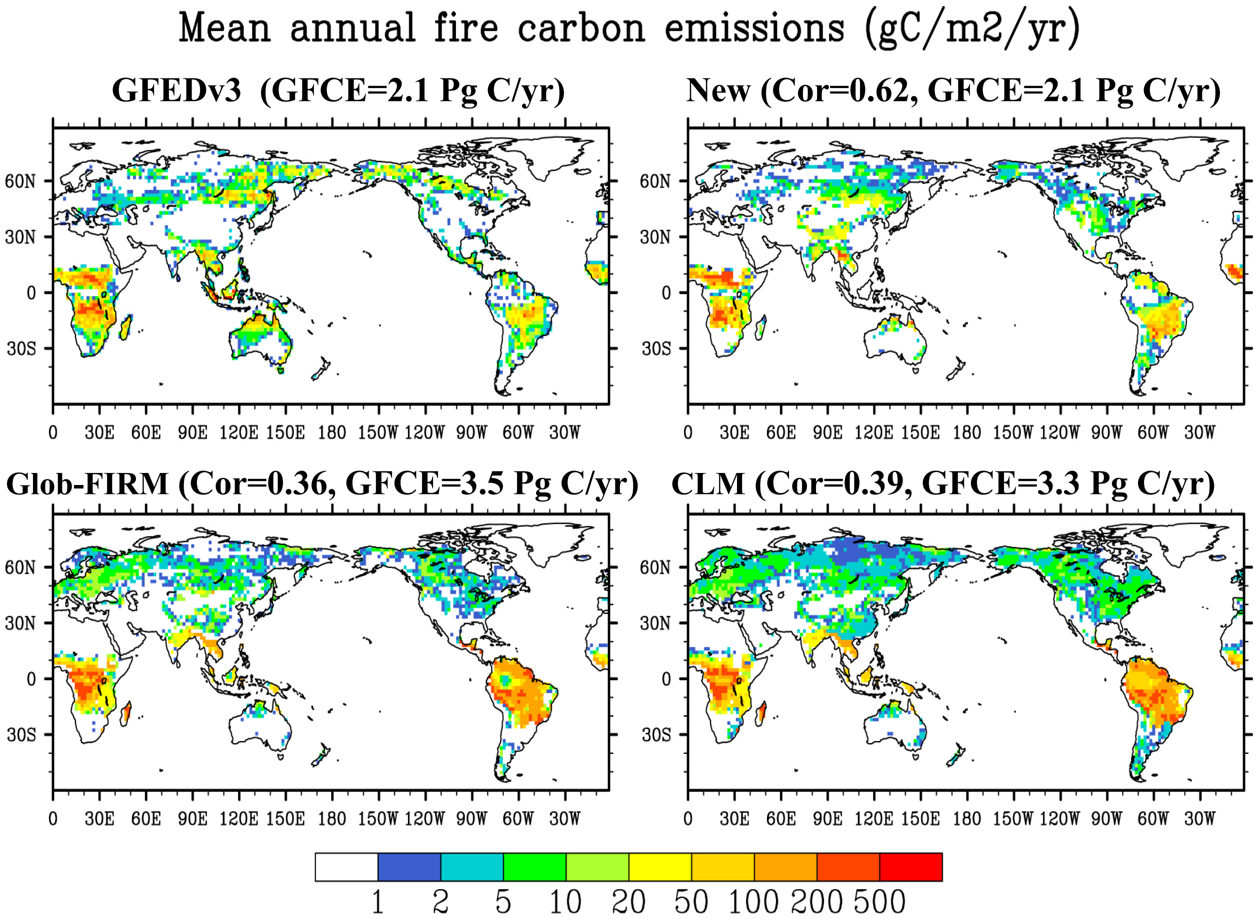


Mean annual burned area fraction (%/yr)



- **Global Total and spatial pattern of our fire scheme are good agreement with obs.**
- **Our fire scheme is more skillful than Glob-FIRM and that used in CLM-DGVM**

• Results (1997-2004): Fire Carbon emissions



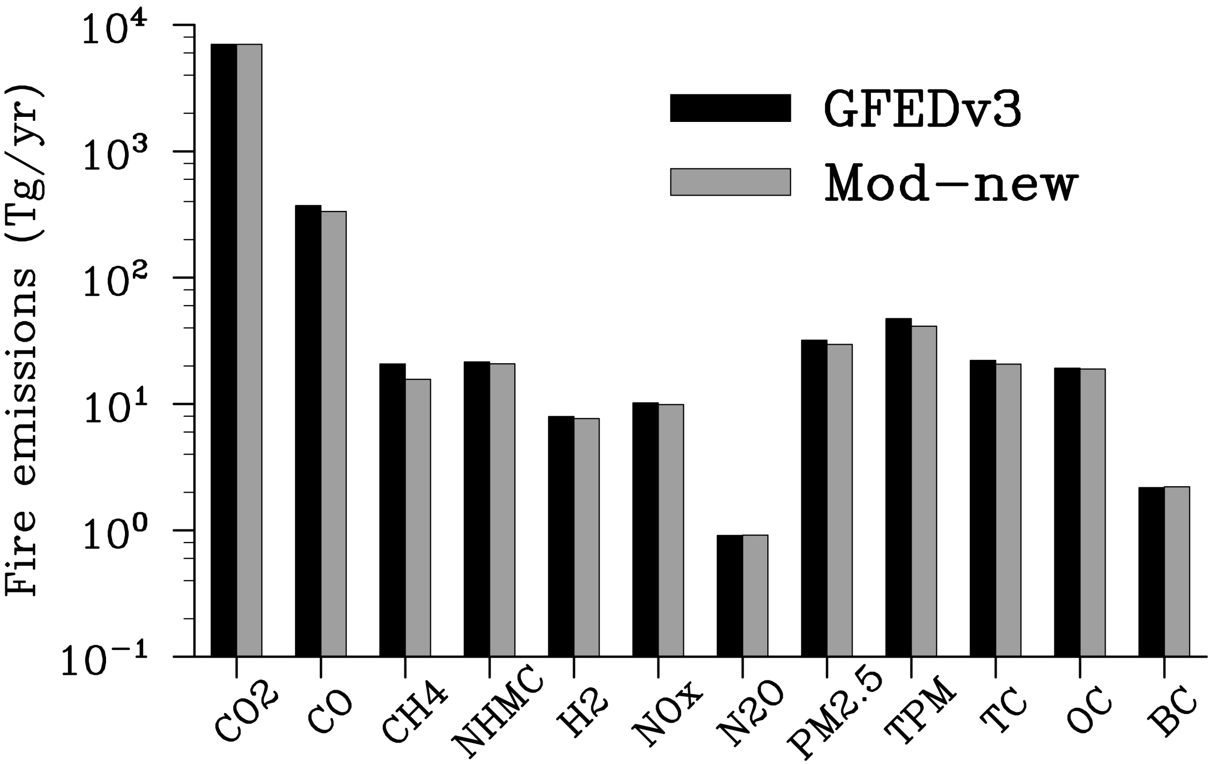
•New has more accurate **global gross (GFCE)** and **spatial distribution** than Glob-FIRM and CLM

•new is more reasonable

•Fire carbon emission /burned area (TgC /Mha):

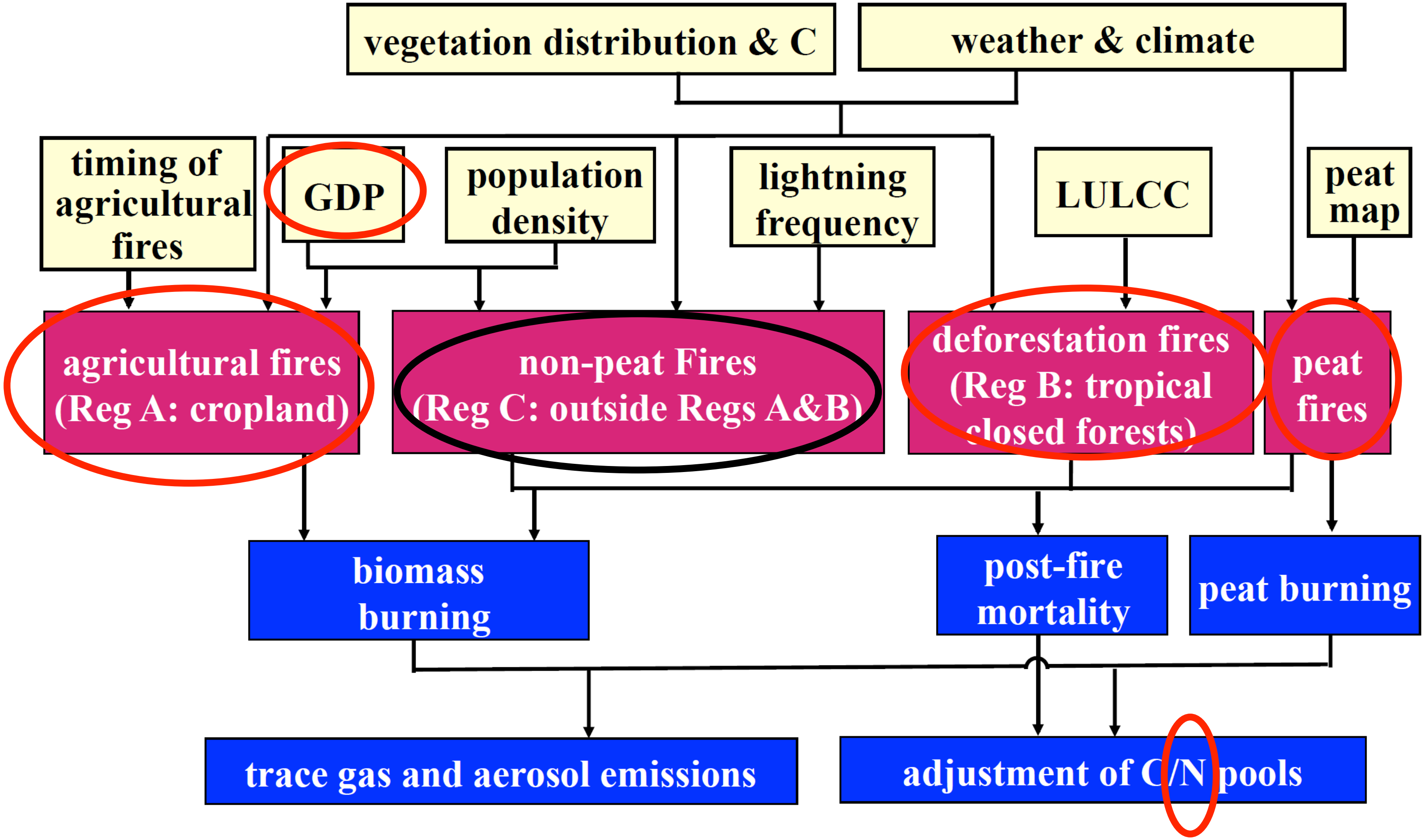
GFEDv3:	**5.5**	**New:**	**5.9**
Glob-FIRM:	**64.8**	**CLM:**	**35.5**

- # Aerosol and trace gas emissions due to fire



- **new fire scheme is good agreement with GFEDv3 product for all types of trace gases and aerosols**
- **Average relative error: 6.02%.**

• Further development of global fire scheme (Li et al. 2013)



- Fire scheme for the IAP-DGVM is used in Reg. C

- This fire scheme was developed with NCAR CLM4 as model platform, tested in CLM4 and now adopted by CLM4.5 official version

Agricultural fires (Reg. A)

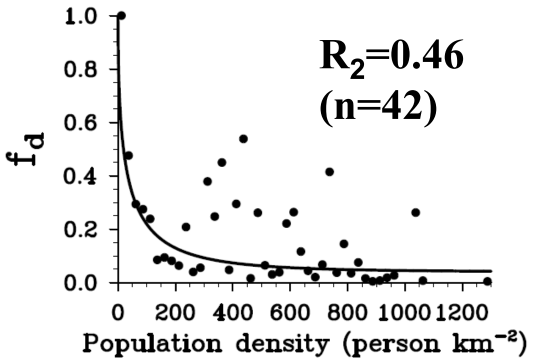
Burned area frac. Fuel availability

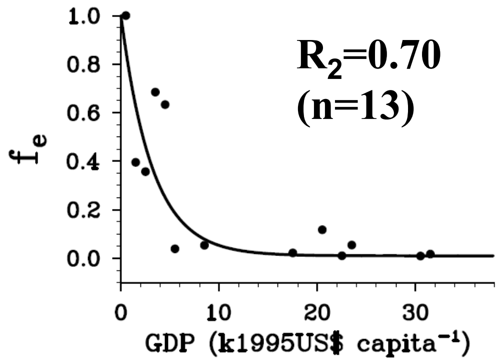
$$f_{ba} = a f_b f_{se} f_t$$

Fire seasonality

Socioeconomic factor

Socioeconomic factor: $f_{se} = f_d f_e$





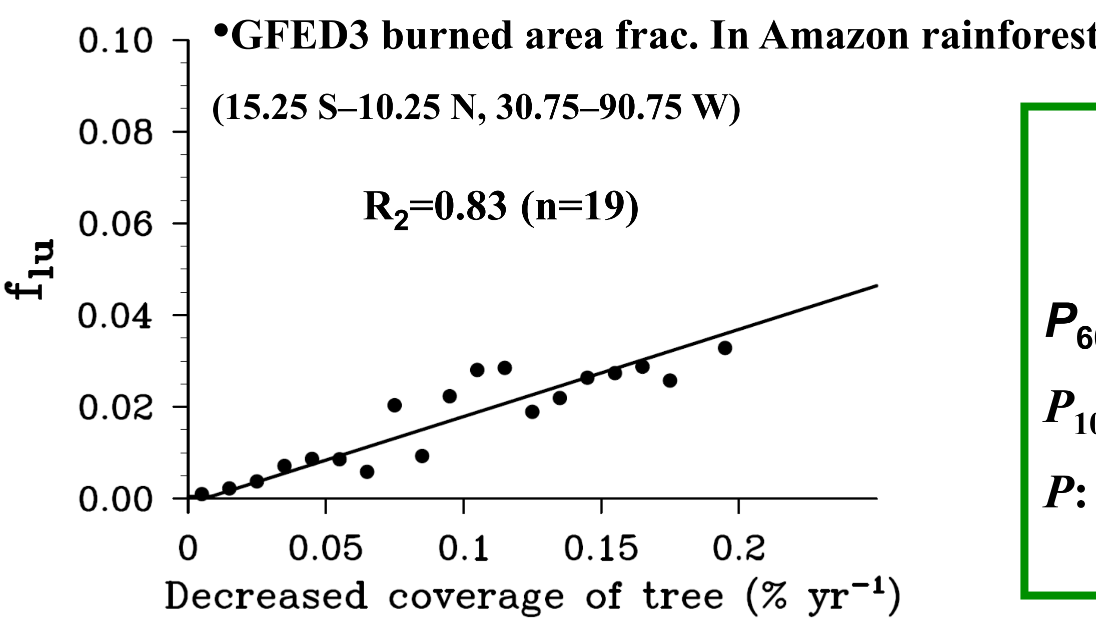
Method: In regions where area fraction of crop PFTs is larger than 50%, we partition 1997−2004 average 0.5° GFED3 burned area fraction divided by f_e over 25 person km^{-2} population density bins, and GFED3 burned area fraction divided by f_d over 1 k1995US$ capita^{-1} GDP bins. Black circles indicate the (normalized) average in bins with sample size >5.

Deforestation fires (Reg. B)

Effect of climate and weather

$$f_{ba} = b f_{lu} f_{cli,d}$$

Effect of deforestation rate



$f_{cli,d} = f(P_{60d}, P_{10d}, P)$

P_{60d}: 60-d running mean of precip.

P_{10d}: 10-d running mean of precip.

P: real-time precip.

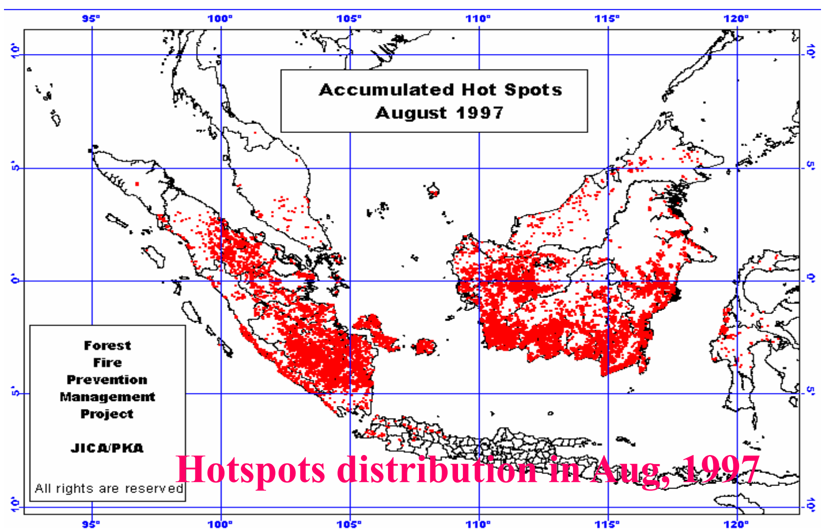
Peat fires

Fuel combustibility

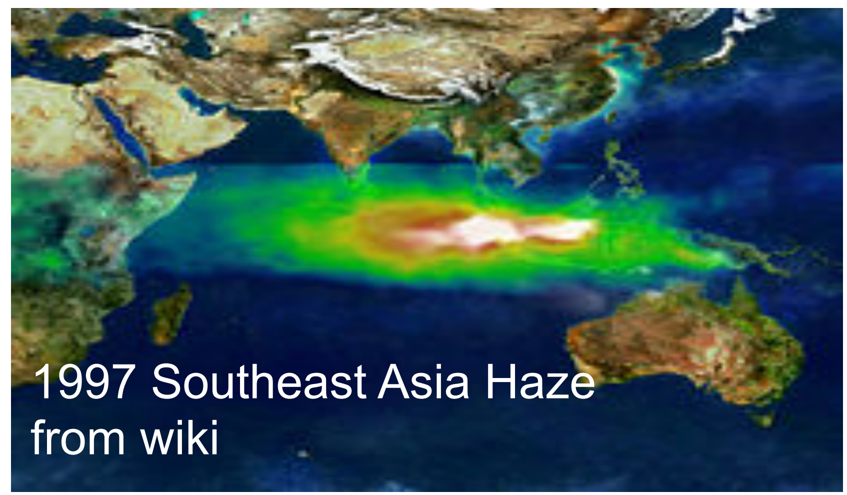
Area frac. of peatland

$$f_{ba} = c f_{cli,p} (1 - f_{sat}) f_{peat}$$

Area frac. of soil exposed to air



Hotspots distribution in Aug, 1997



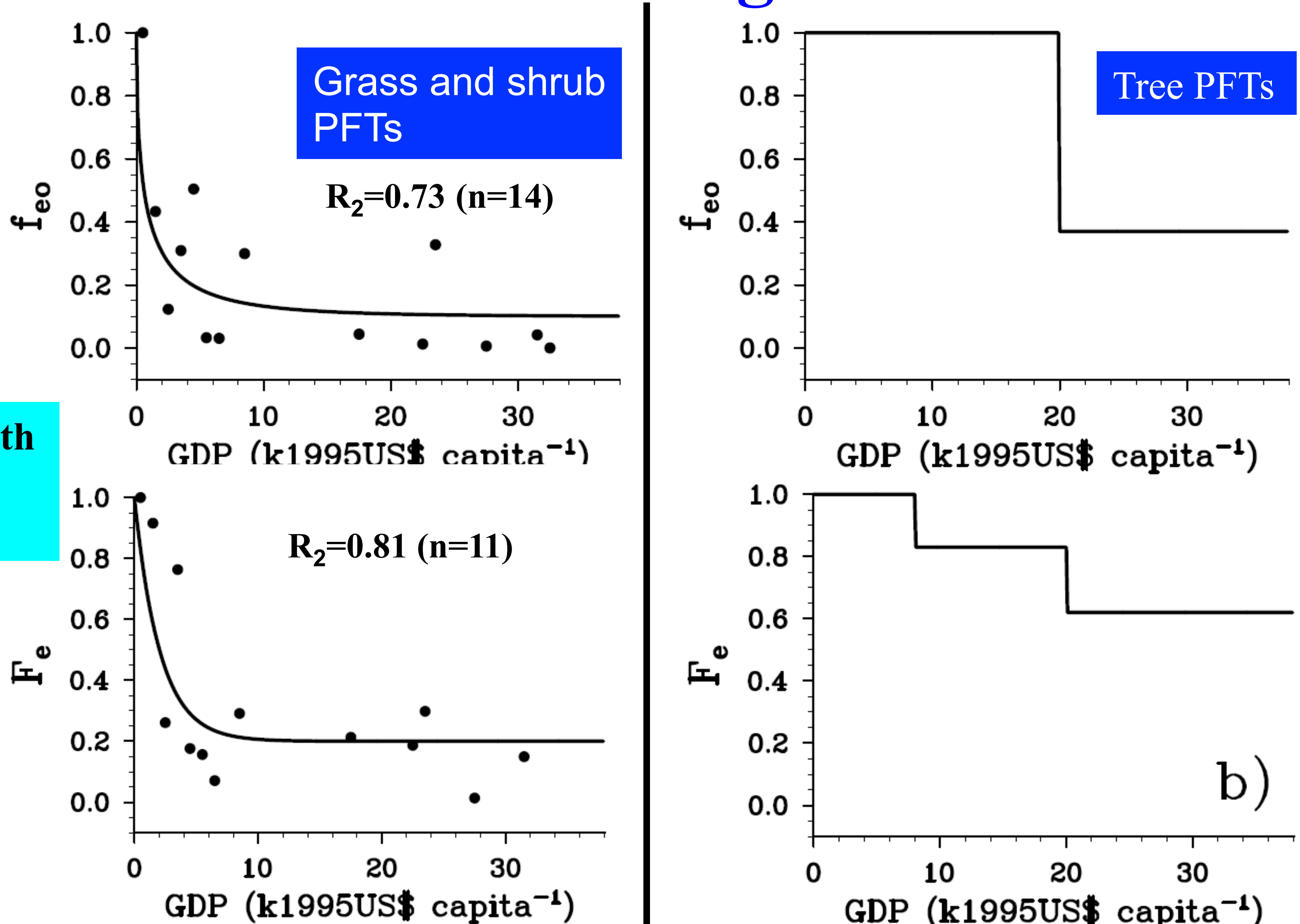
1997 Southeast Asia Haze
from wiki

Economic effect on fire in Reg. C

Effect on fire occurrence

For regions with pop. den. >0.1 person/km²

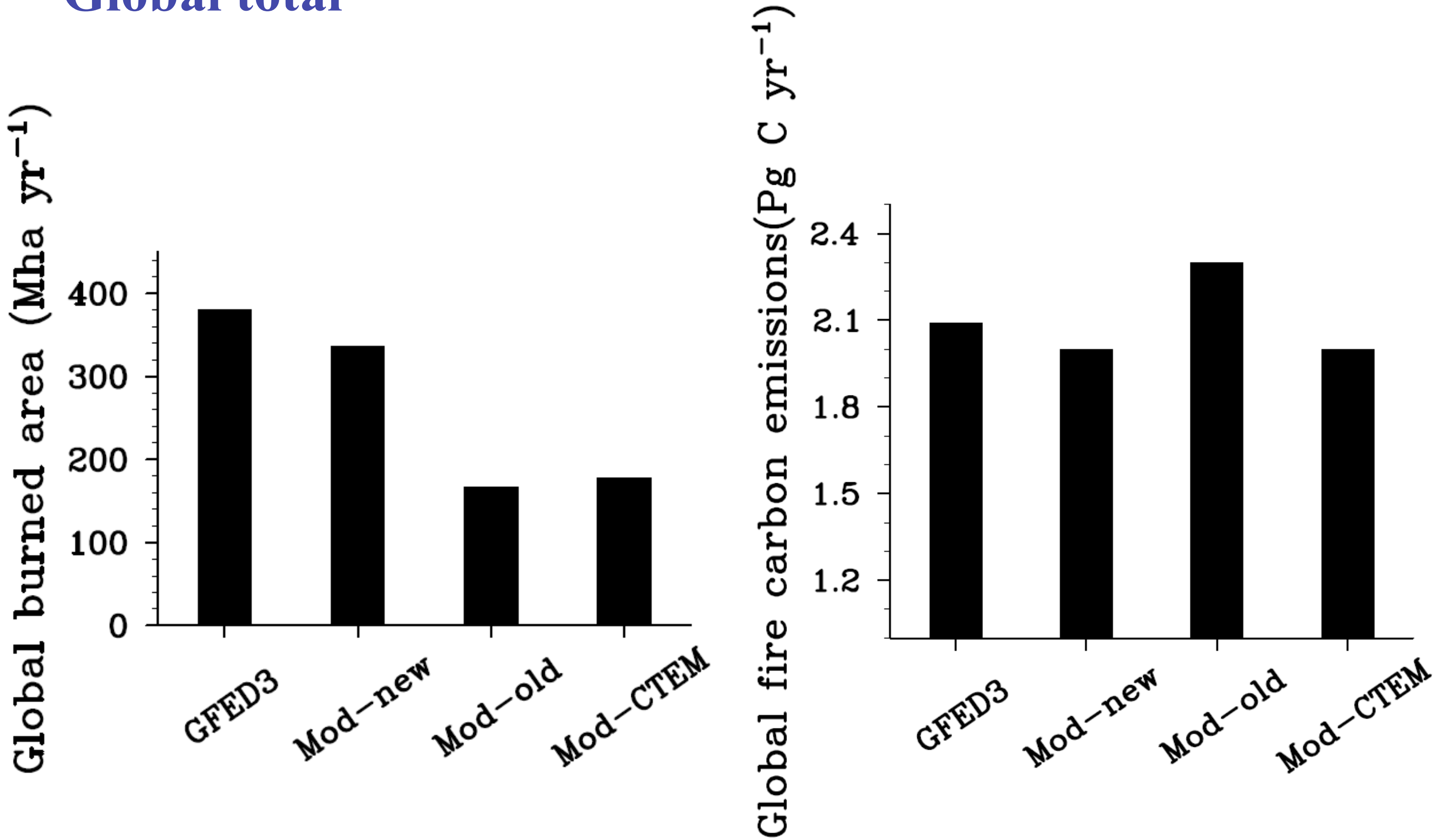
Effect on fire spread



Method similar to that used for socioeconomic factor of agricultural fires, but for grass and shrub PFTs and Tree PFTs.

• Performance in CLM4 (1997-2004)

• Global total



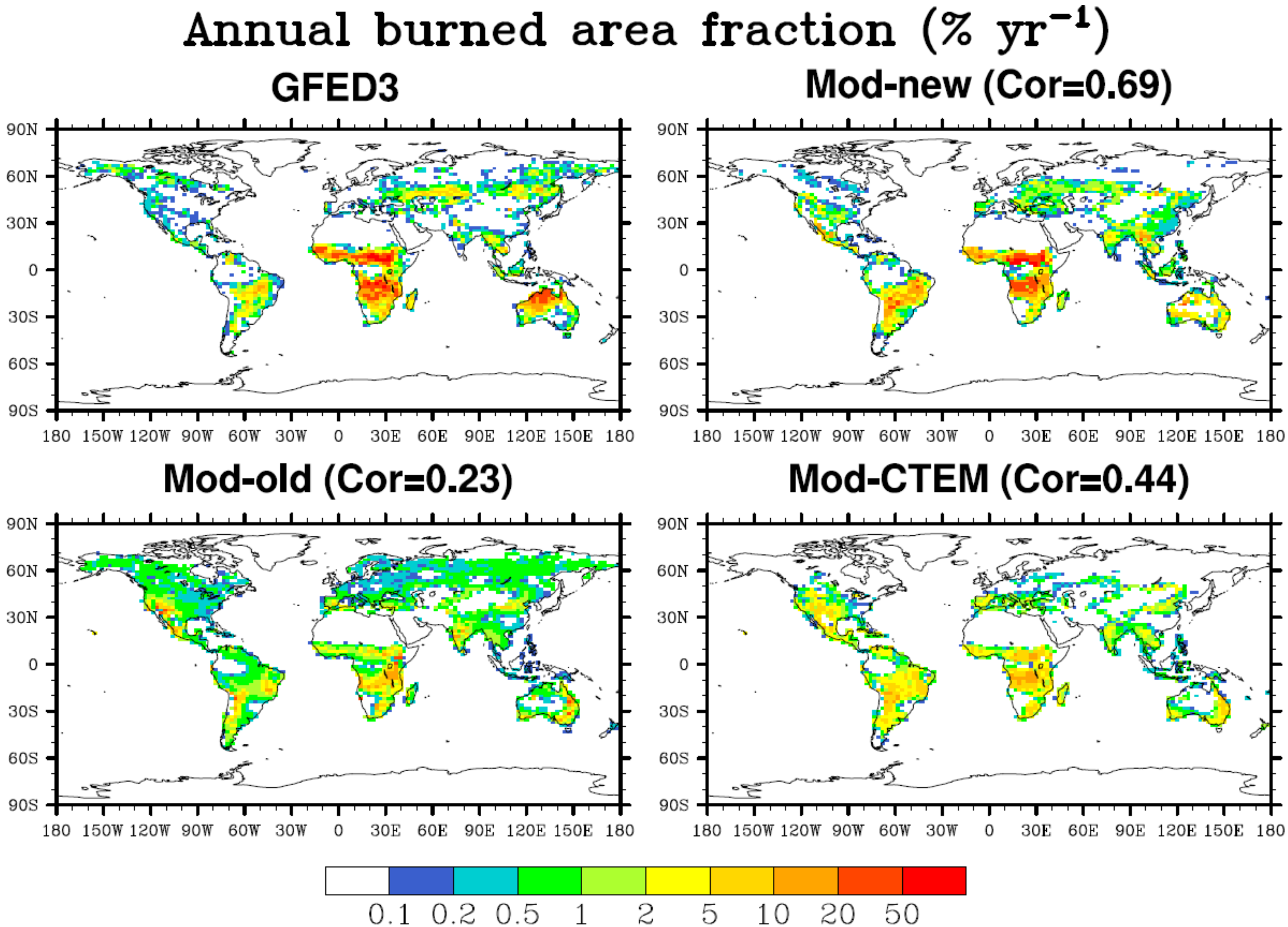
Mod-new: our fire model ; fire model adopted in official CLM4.5

Mod-CTEM: Kloster et al.(2010), had planned to be introduced in CLM4.5

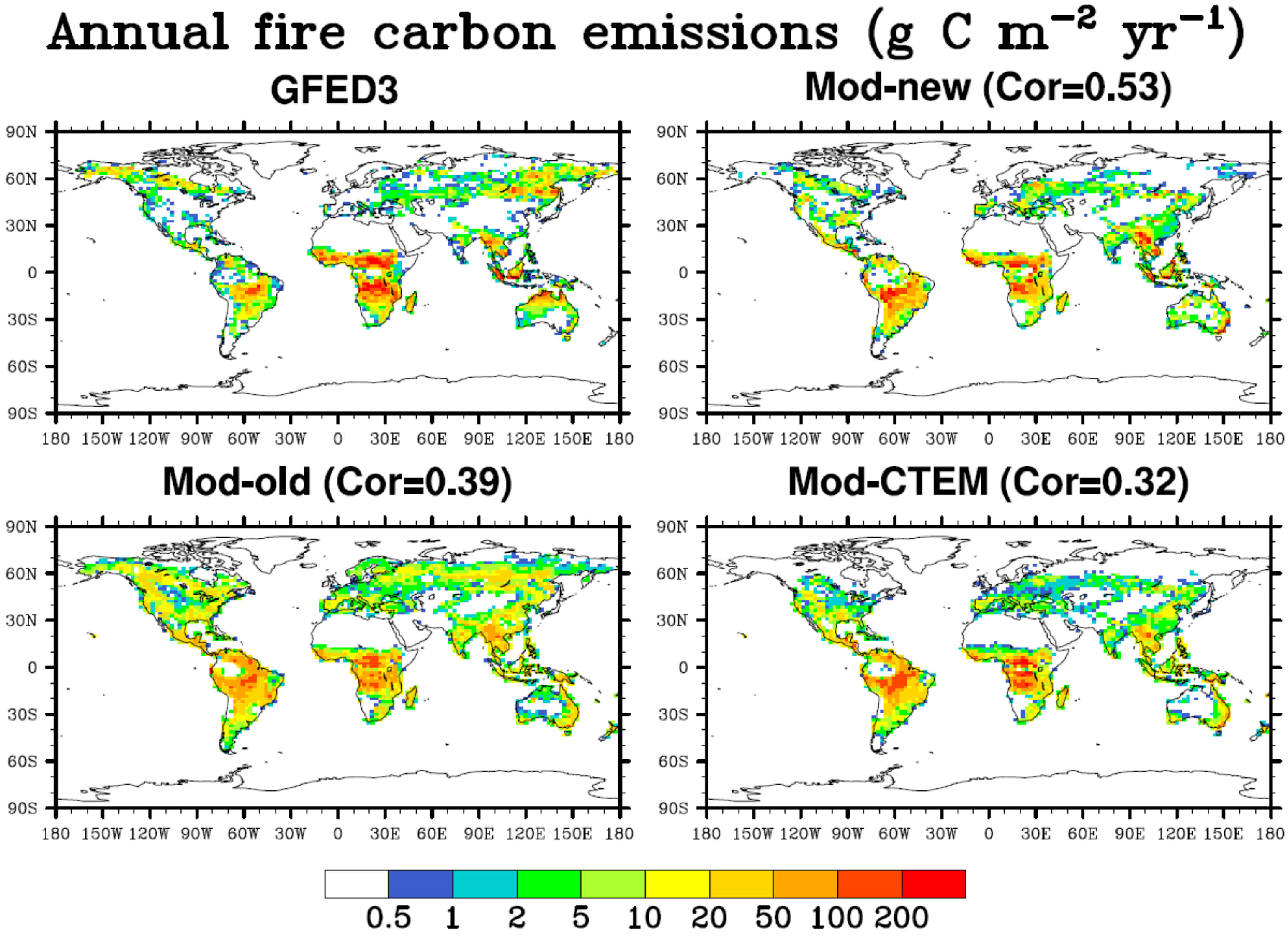
Mod-old: Modified Glob-FIRM; fire model in official CLM4

Global spatial distribution of burned area fraction

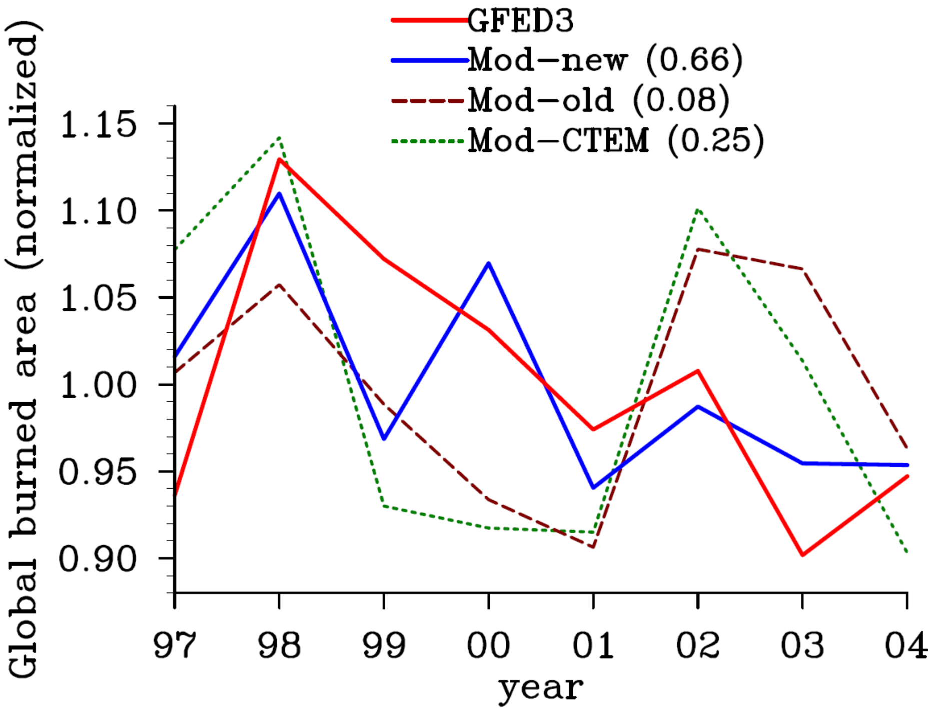
Cor: global spatial correlation between obs and simulations

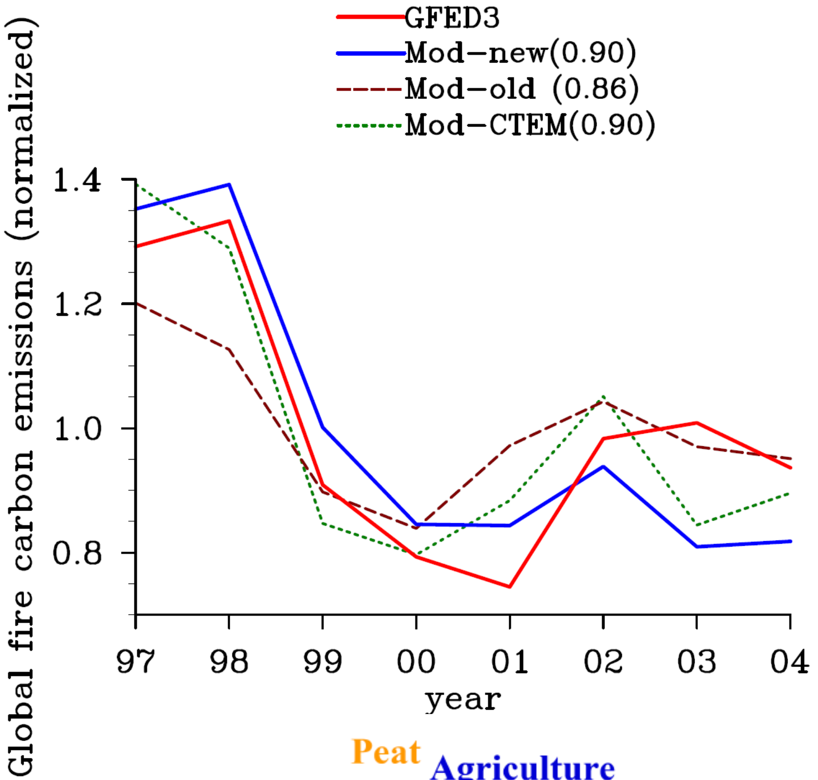


Global spatial distribution of fire carbon emissions

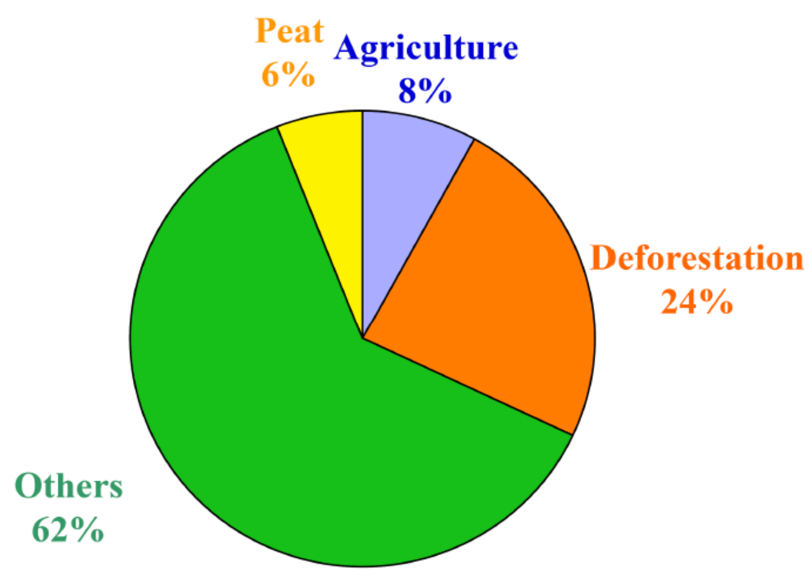


Interannual variability

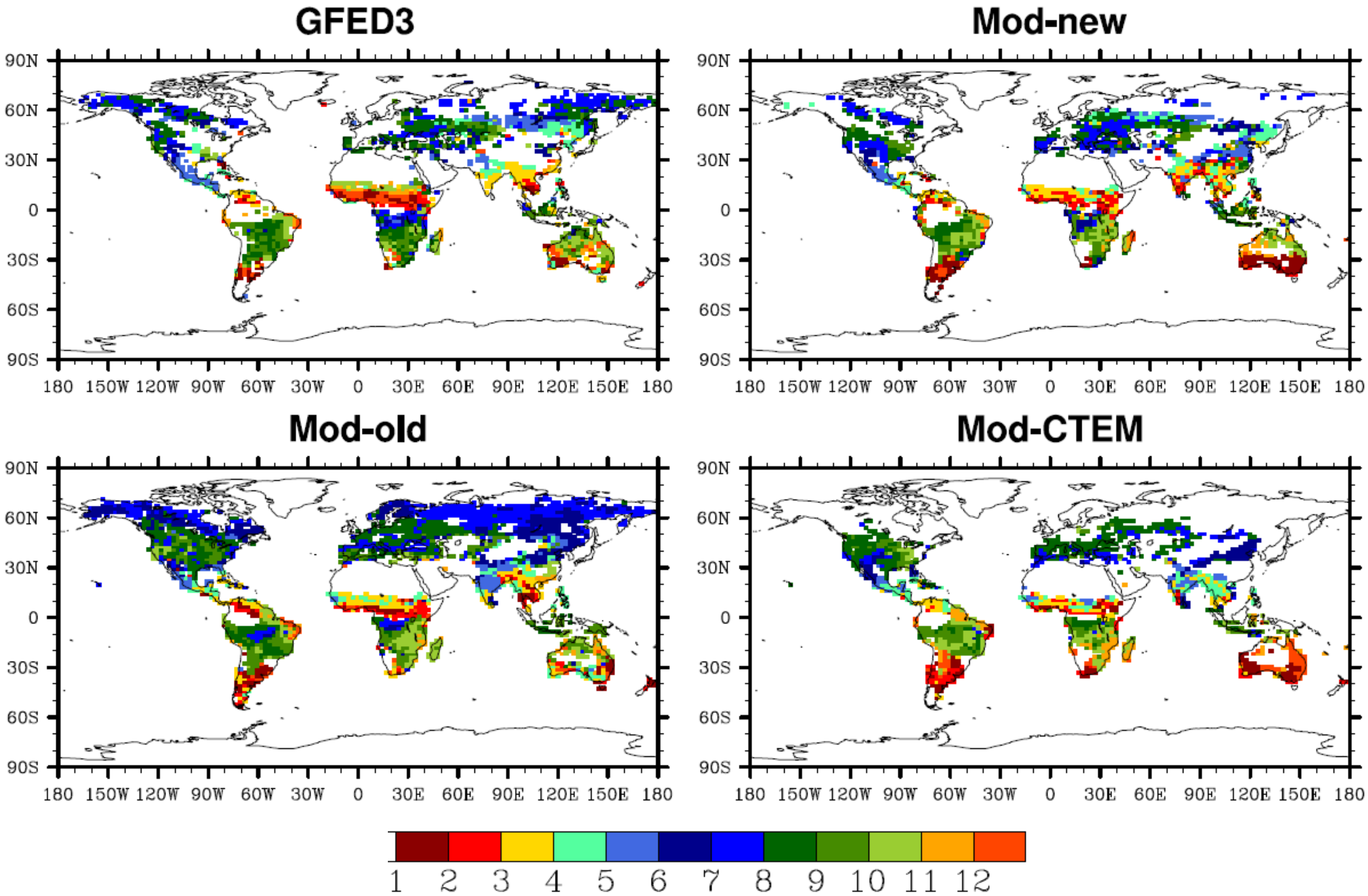




- **Contributions of global carbon emissions from different sources**



Seasonality of burned area fraction



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Quantifying the impact of fire on net C balance of terrestrial ecosystems during the 20th Century in CLM4.5 (Li et al., to be submitted)

•Introduction

•General background:

- Fire direct and indirect effects on NEE (Kasischke et al, 1995):

  Fire direct effect: fire carbon emissions (immediately during biomass burning)

  Fire indirect effect: fire-induced change for NEP and Clh (maybe last very long)

- $NEE = -NEP + C_{lh} + C_{fe}$

  NEE: net ecosystem exchange, negative signs indicates a net C uptake by land;

  C_{lh} : C loss due to land use/cover change; C_{fe}: fire carbon emissions

  NEP=NPP-Rh; NPP=GPP-Ra

• Earlier works

- On a global scale: focused on fire direct effects (present-day; big-uncertainty in historical reconstructions)
- All earlier estimates about fire total effect and fire indirect effect are on regional or site-level scale, except Ward et al. (2012) who estimated the fire effect on global C_{lh}

•Our aim: provide the first quantitative assessment about fire effect on net eco. C balance

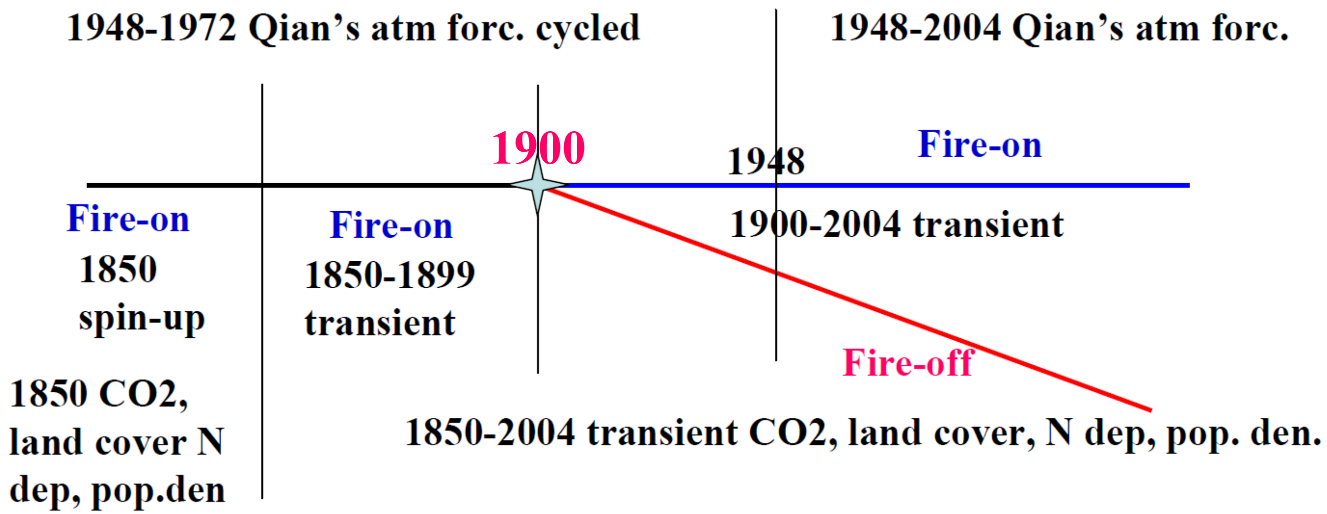
Data and methods

•Model-platform:

CLM4.5-BGC (CLM4.5 biogeochemistry version)

•Simulations: fire-on and the 20th C fire-off sims.

Resolution: 1.9º (lat) × 2.5º (lon) ; 30-min



•Model input data:

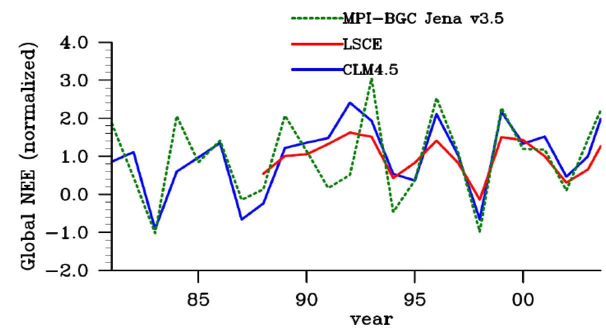
Atm forcing (Qian et al., 2004), pop. den, peat frac., GDP, CG lightning, LULCC data, CO2, aerosols deposit …

•Evaluation of CLM4.5 present-day global performance and benchmark data

Avg: average of global total, Unit is Mha/yr for burned area and Pg C/yr for others;
T-Cor: temporal cor. of global total; S-Cor: global spatial cor; * and ¯ : 95% and 90% conf. lev.

Variables	Period	Statistics	CLM4.5	Benchmarks	Source for Benchmarks
Burned area	1997-2004	Avg	322	380	GFED3 (Giglio et al., 2010 ; van der Werf et al. 2010)
		T-Cor	0.63*		
		S-Cor[a]	0.71*		
Fire carbon emissions	1997-2004	Avg	2.1	2.1	
		T-Cor	0.91*		
		S-Cor	0.50*		
NEE	1990s	Avg	-0.8	-1.0±0.6	IPCC AR4 (Denman et al., 2007)
				-1.1±0.9	IPCC AR5 (Ciais et al., 2013)
	1988-2004	T-Cor	0.74*		LSCE (Chevallier et al., 2010)
	1981-2004	T-Cor	0.75*		MPI-BGC Jena v3.5 (Röedenbeck et al., 2006, C. Röedenbeck, p. c., 2013)
GPP	1982-2004	Avg	127	122	Jung et al. (2011); M. Jung (personal communication, 2013)
		T-Cor	0.38¯		
		S-Cor	0.90*		
	2000-2004	Avg	130	110	Zhao et al. (2005); Zhao and Running (2010)
		T-Cor	0.87*		
		S-Cor	0.88*		
NPP	2000-2004	Avg	54	54	
		T-Cor	0.75*		
		S-Cor	0.81*		

CLM4.5 present-day fire sim. is similar to that in CLM4



GPP from 10 terrestrial biosphere models of IPCC AR5 (1982-2007) (Piao et al. 2013)

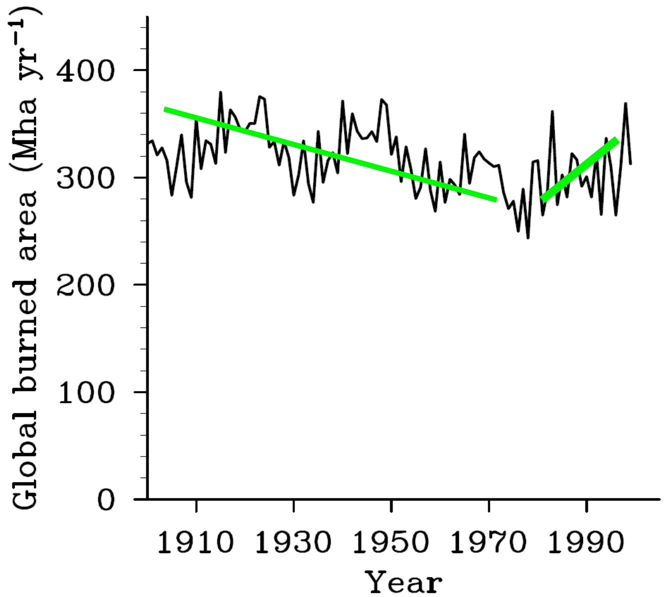
Global total: 133±15 Pg C/yr Temp. cor: <0.4

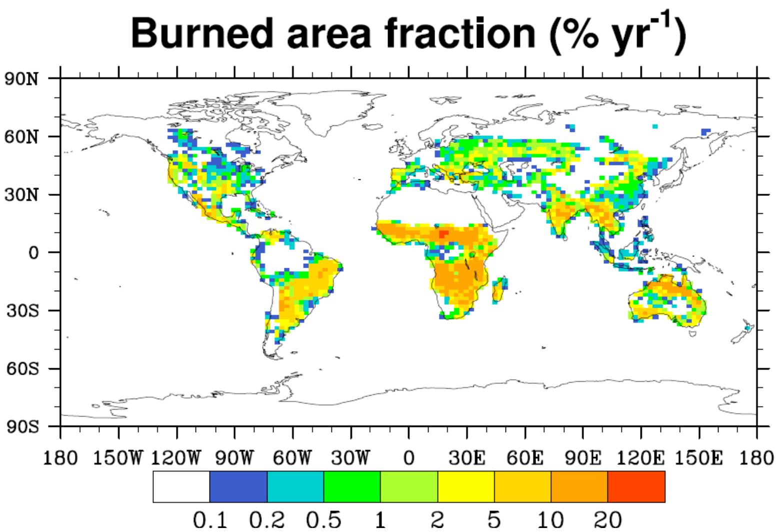
CLM4.5 can overall reasonably simulate the global total, temporal variability, and large-scale spatial pattern of contemporary fire and terrestrial carbon fluxes.

• Simulated burned area in the 20th century

Global total: 316 Mha/yr

Smaller than ~500 Mha/yr from Mouillot and Field (2005; MF05), but that MF05 simulated 608 Mha/yr at the end of the 20th is about 1.5 times of GFED3 suggests a overestimation in its global total for the 20th century





Long-term trend is similar to that from MF05 which was derived from tree-ring reconstructions, stand age in contemporary stands, and historical writing and data regarding fire regimes or land use change.

Spatial pattern is similar to that from MF05

Impact of fire on net C balance: 20th Century average of global total

Variables	Fire-on − Fire-off	Fire-on	Fire-off
NEE	1.0*	-0.1	-1.1
Fire carbon emissions	1.9*	1.9	0.0
-NEP+C_{lh}	-0.9*	-2.0	-1.1
NEP	0.8*	3.0	2.3
NPP	-1.9*	49.6	51.6
Rh	-2.7*	46.6	49.3
GPP	-5.0*	118.9	123.9
Ra	-3.1*	69.3	72.4
C_{lh}	-0.1	1.0	1.1

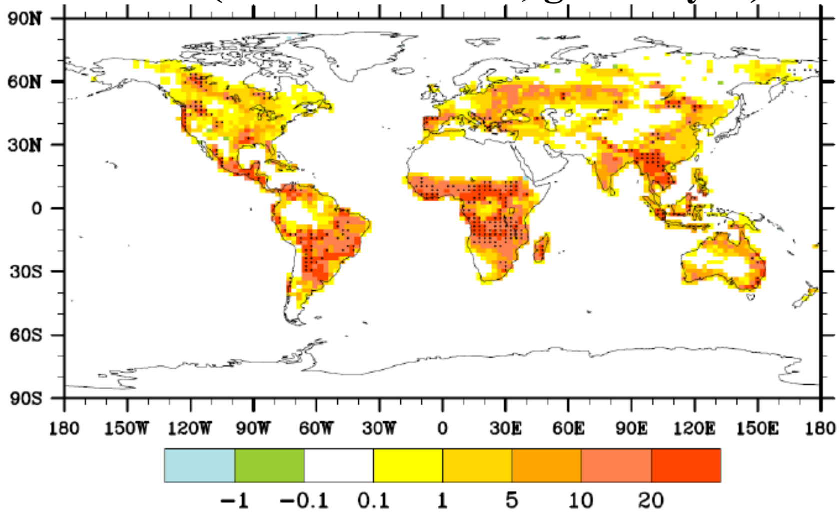
***difference in the means between fire-on and fire-off simulations passed student t-test at α=0.05 sig. level.**

Unit is Pg C/yr

Fire significantly decreases net carbon gain of the global terrestrial ecosystems by 1.0 Pg C/yr average across the 20th century, which is the result of 42% of fire carbon emissions (1.9 Pg C/yr) offset by fire indirect effects (–0.9 Pg C/yr)

Impact of fire on net C balance: spatial pattern

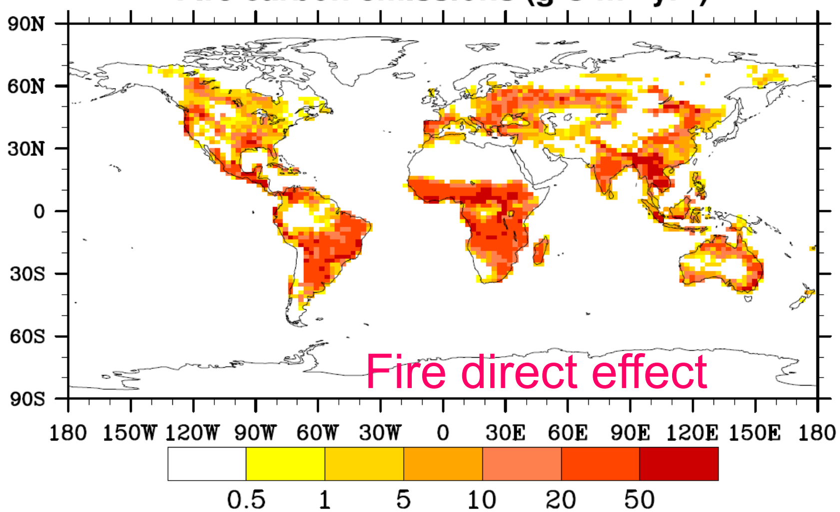
ΔNEE (fire-on – fire-off; g C m^{-2} yr^{-1})



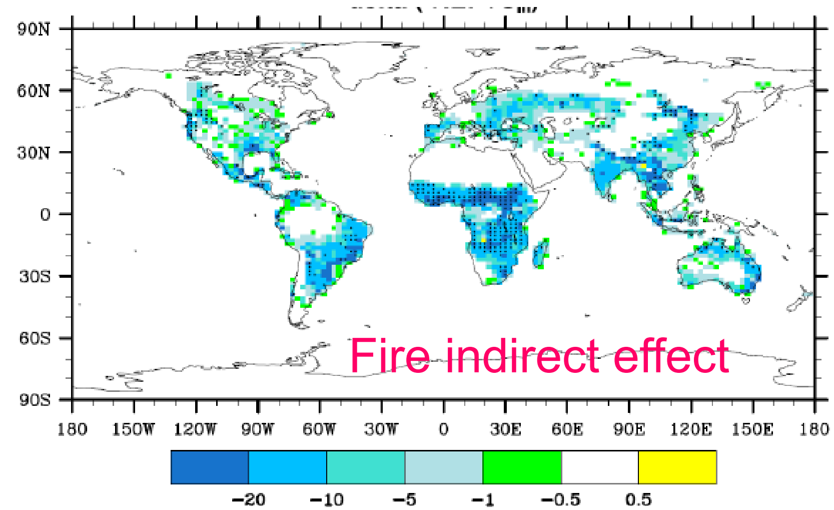
- **Fire generally decreases carbon gain in post-fire regions because fire direct effect is stronger than the indirect effect**

- **Fire total and indirect effects are significant over tropical savannas in Africa and South America and part of forests in North America and the east of Asia, where fire direct effect is also strong**

Fire carbon emissions (g C m^{-2} yr^{-1})

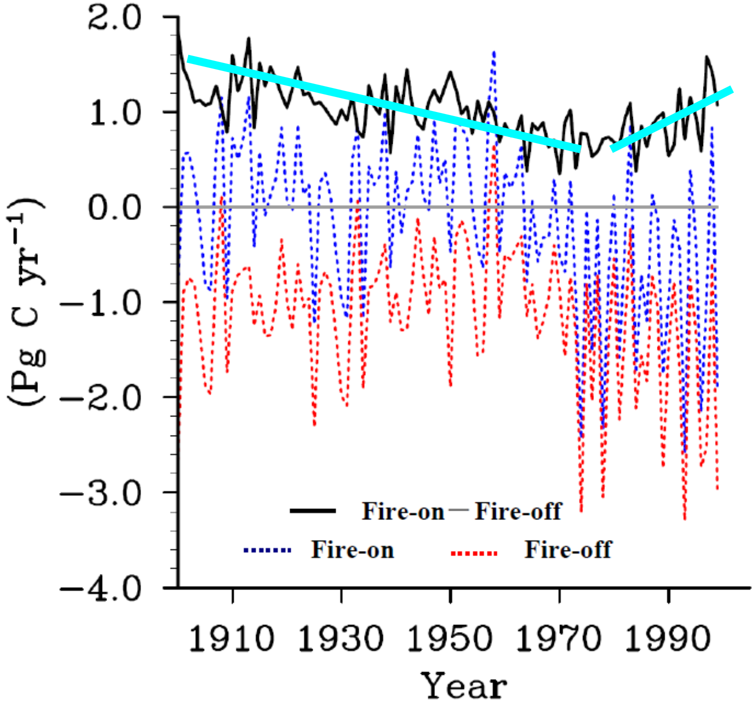


Δ(–NEP+Clh) (g C m^{-2} yr^{-1})

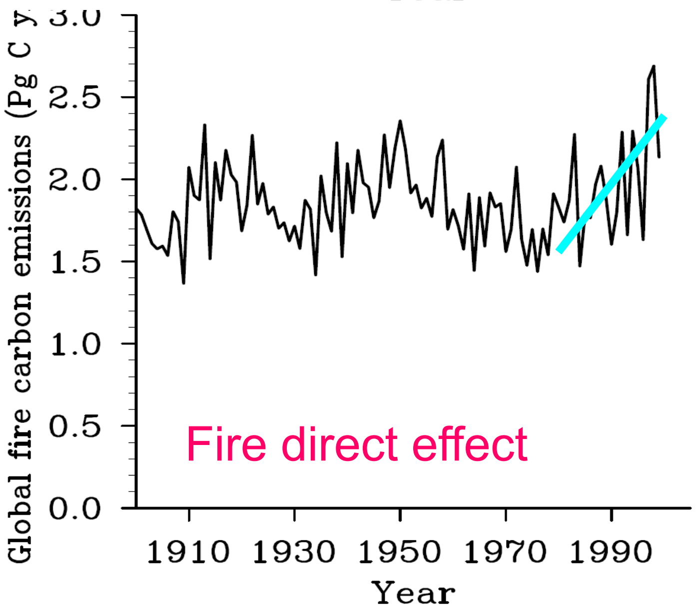


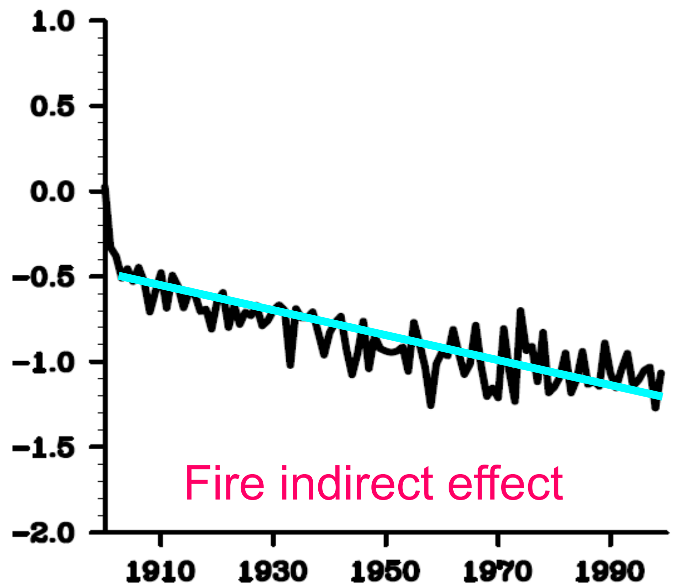
Differences in average with t-test at α=0.05 significance level are stippled for fire total and indirect effects

Impact of fire on net C balance: temporal pattern



- Fire effect on NEE significantly decreases prior to 1971 (trend: -0.08 Pg C 10yr-1) due to increasing fire indirect effect, and increases since 1972 (trend: 0.18 Pg C 10yr-1) due to increasing fire carbon emissions





Near future works

- **fire model development**

  Fire duration

  Human dimension

  Fire effect on soil organic carbon outside peat land

- **fire model application**

Quantify and understand the impact of fire on global veg. distribution and climate (Temperature and precipitation) during the 20th century

Thank you !

Fire parameterization

Li, F., Zeng, X. -D., and Levis, S.: A process-based fire parameterization of intermediate complexity in a Dynamic Global Vegetation Model, Biogeosciences, 9, 2761–2780, doi:10.5194/bg-9-2761-2012, 2012a.

Li, F., Levis, S., and Ward, D. S.: Quantifying the role of fire in the Earth system – Part 1: Improved global fire modeling in the Community Earth System Model (CESM1), Biogeosciences, 10, 2293-2314, doi:10.5194/bg-10-2293-2013, 2013.

Thonicke, K., Venevsky, S., Sitch, S., and Cramer, W.: The role of fire disturbance for global vegetation dynamics: Coupling fire into a Dynamic Global Vegetation Model, Global Ecol. Biogeogr., 10, 661– 677, 2001.

Quantifying global-scale fire impact

Bond, W. J., Woodward, F., and Midgley, G. F.: The global distribution of ecosystems in a world without fire, New Phytol., 165, 525– 538, doi:10.1111/j.1469-8137.2004.01252.x, 2004.

Ward, D. S., Kloster, S., Mahowald, N. M., Rogers, B. M., Randerson, J. T., and Hess, P. G.: The changing radiative forcing of fires: global model estimates for past, present and future, Atmos. Chem. Phys., 12, 10857-10886, doi:10.5194/acp-12-10857-2012, 2012.

Li, F., Bond-Lamberty, B., Slevis, and S.: Quantifying the role of fire in the Earth system. Part II: Impact on the net carbon balance of global terrestrial ecosystems for the 20th century, Biogeosciences, 2013, to be submitted

DGVM

Zeng X. D., Li, F., and Song, X.: Development of the IAP Dynamic Global Vegetation Model, Adv. Atmos. Sci., 2013, in press.

Levis, S., Bonan, G. B., Vertenstein, M., and Oleson, K. W.: The Community Land Model’s dynamic global vegetation model (CLM- DGVM): Technical description and user’s guide, NCAR Tech. Note TN-459_IA, Terrestrial Sciences Section, Boulder, Colorado, 2004.

Moorcroft, P. R., Hurtt, G. C., and Pacala, S. W.: A method for scaling vegetation dynamics: The ecosystem demography model (ED), Ecol. Monogr., 71, 557– 586, 2001.

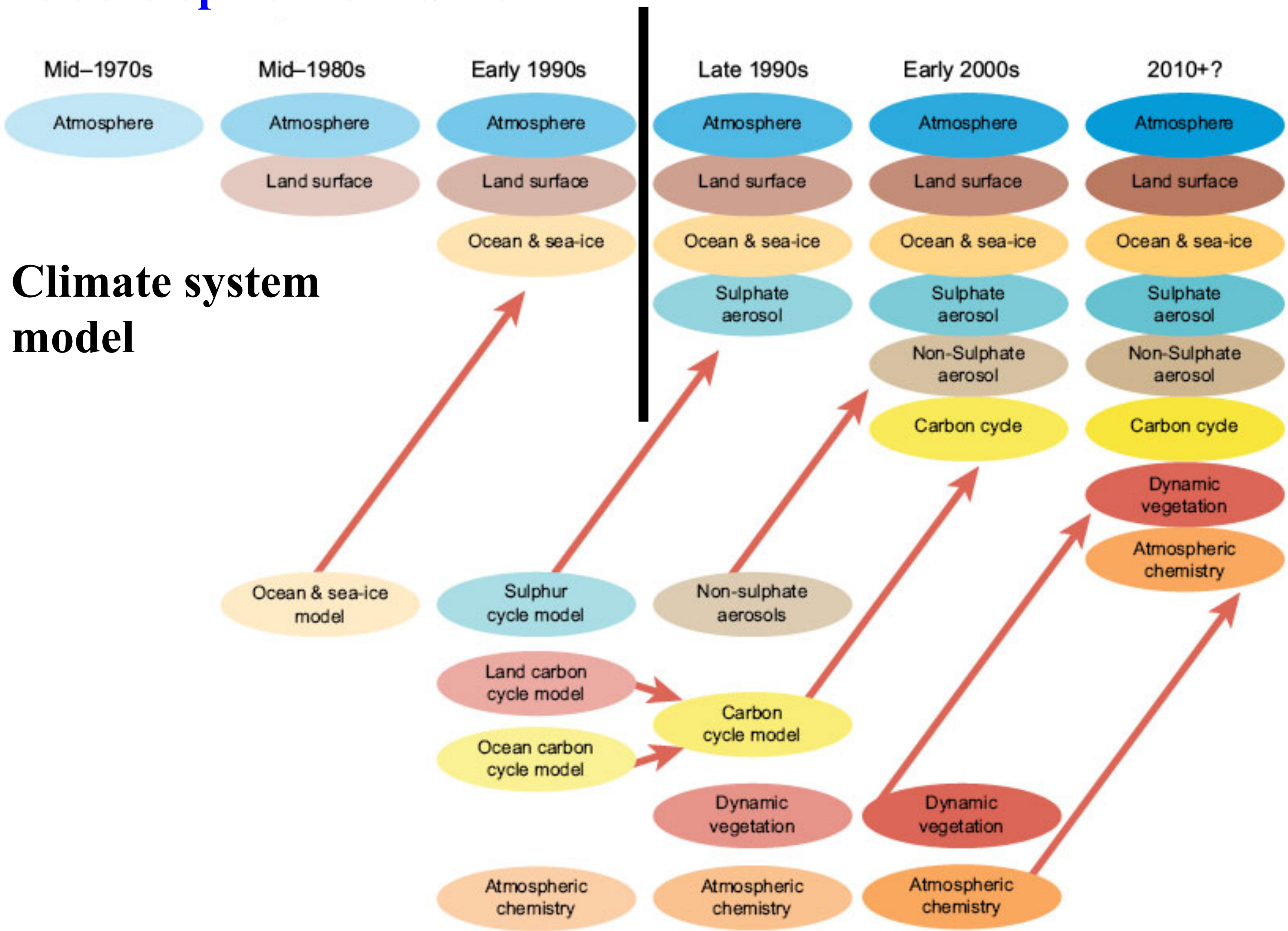
Land surface model

Oleson, K.W., and coauthor: Technical description of version 4.5 of the Community Land Model (CLM), NCAR Technical Note NCAR/TN-503+STR, 434 pp, 2013.

ESM

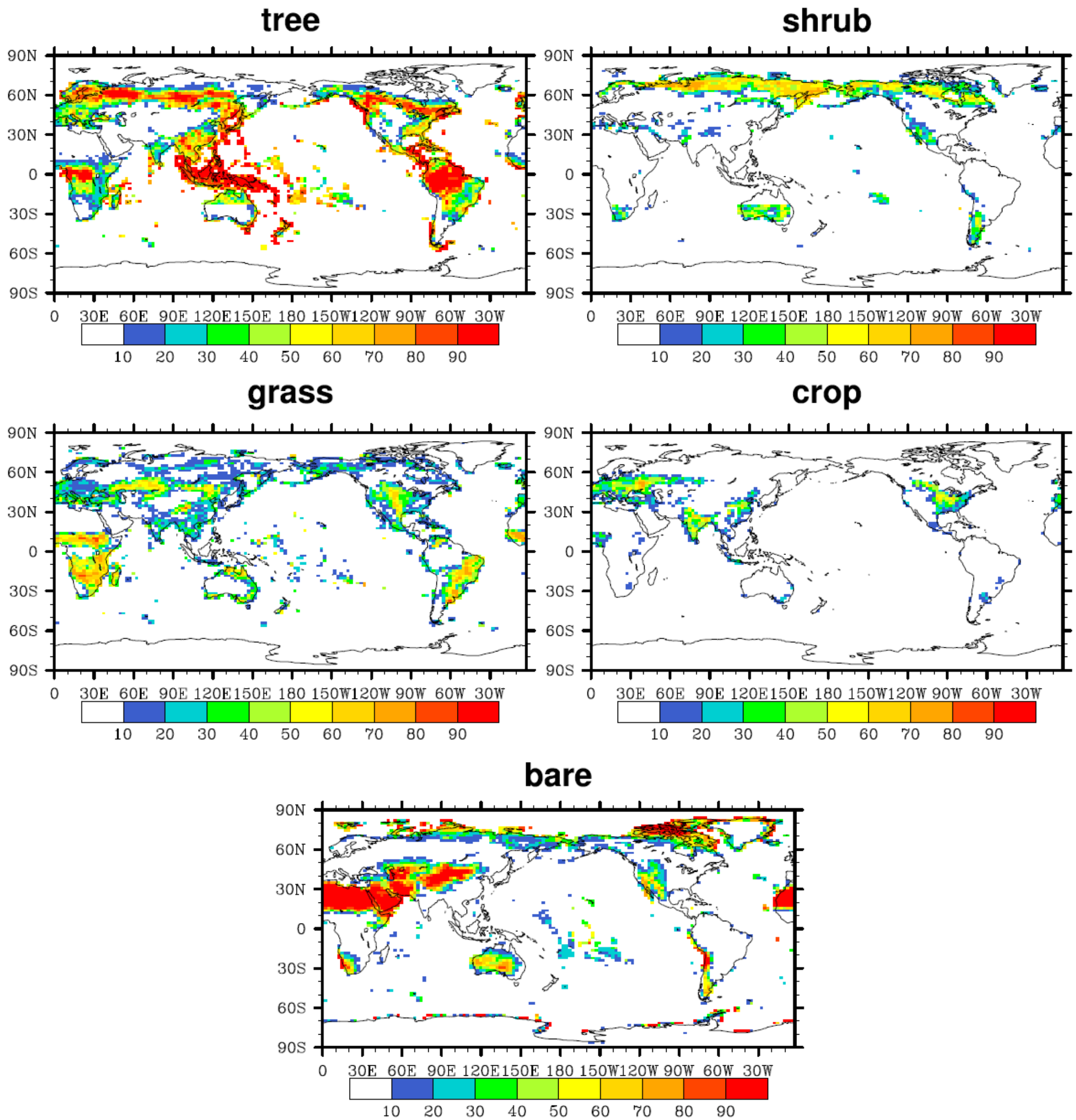
http://www.cesm.ucar.edu/events/tutorials/ ; http://cmip-pcmdi.llnl.gov/cmip5/

The development of ESMs



From IPCC (2001a)

- **Existing intermediate process-based fire parameterizations have some shortcomings**:
  - **Glob-FIRM: not take into account**
    - **Availability of ignition sources**
    - **Impact of wind speed on fire spread**
    - **Combustion incompleteness of plant tissues in the post-fire region**
  - **CTEM-FIRE:**
    - **Constant probability of human-caused ignition and cloud-to-ground lightning fraction (0.5 and 0.25, globally)**
    - **self-inconsistent estimation scheme of burned area**
    - **framework of fire occurrence part →underestimate burned area in tropical savanna**.


tree
shrub
grass
crop
bare
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
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90W
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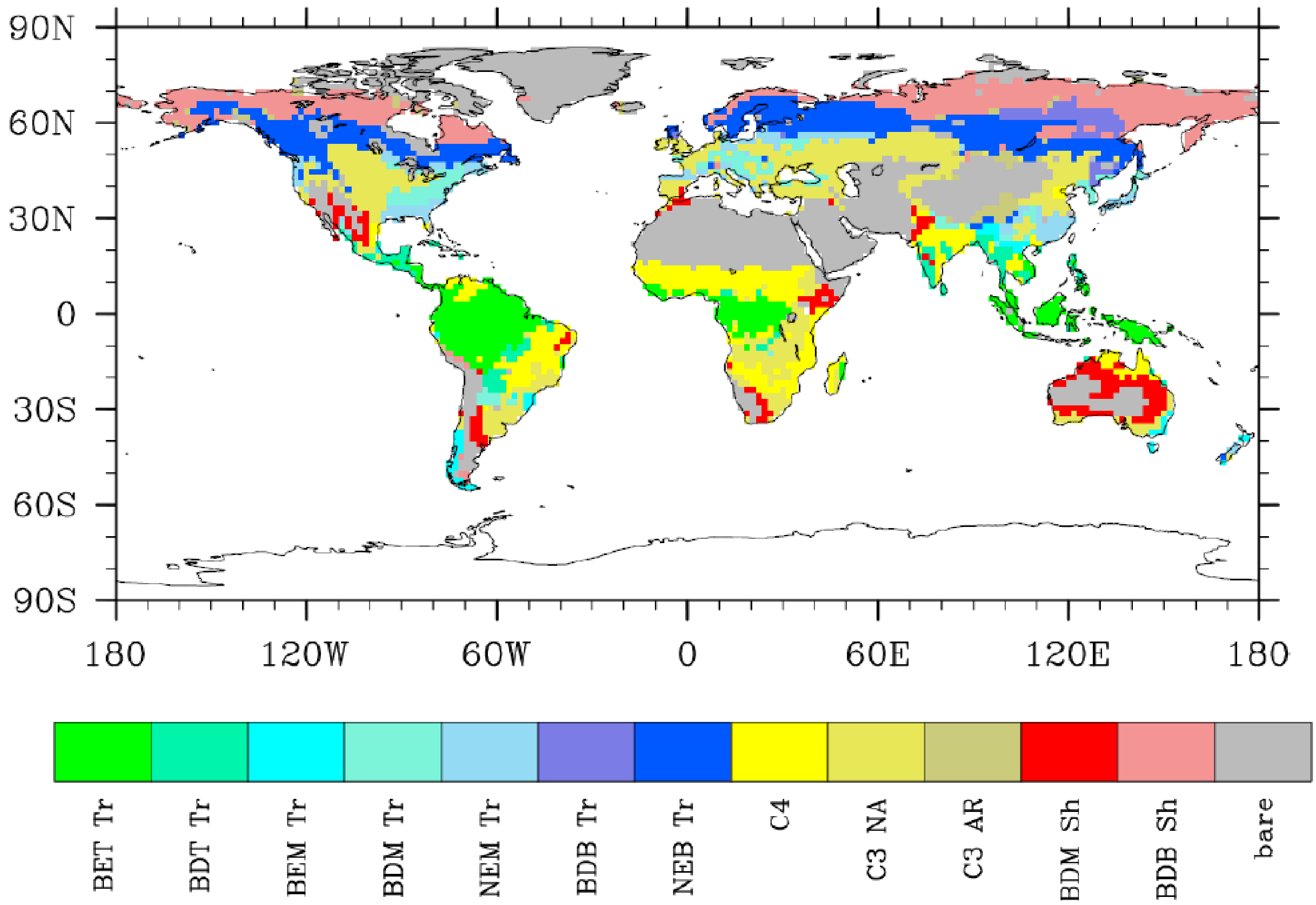
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BET Tr
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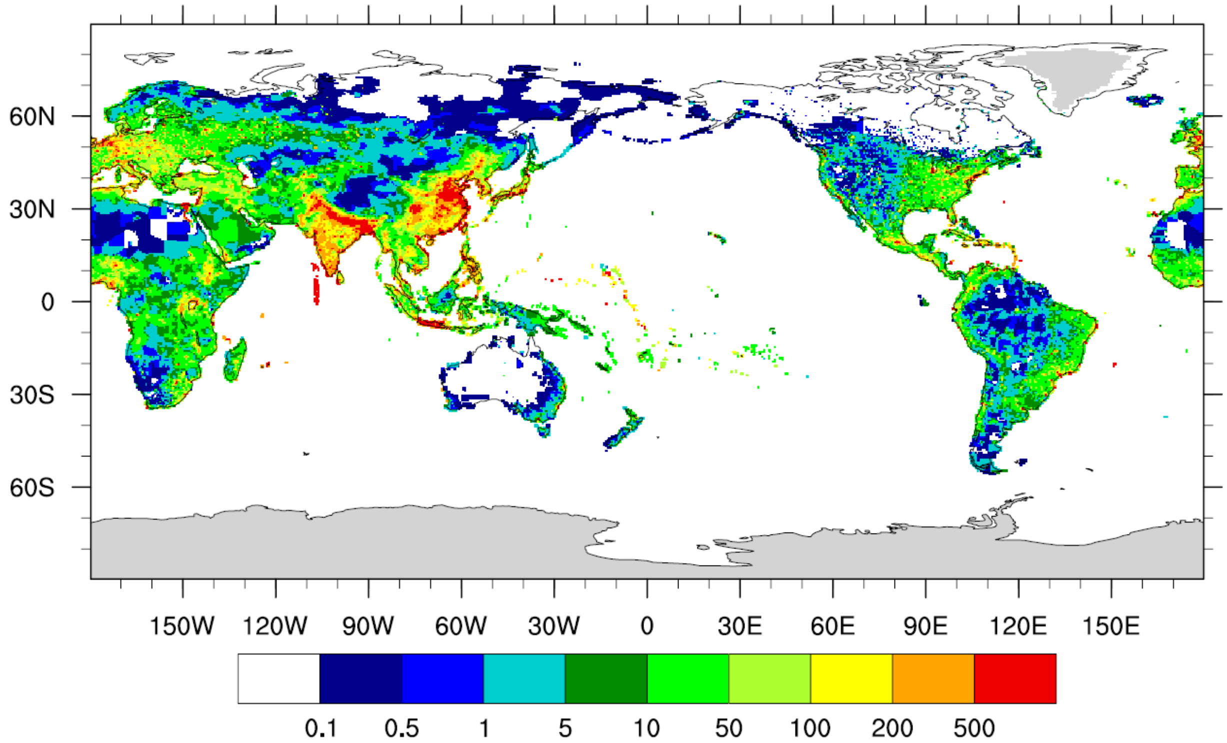
C3 AR
BDM Sh
BDB Sh
bare


60N
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30W
0
30E
60E
90E
120E
150E
0.1
0.5
1
5
10
50
100
200
500

•Establishment of woody PFTs

Correction of area available for est.

$$\Delta P_i = [\Delta P_{max}(1-e^{-5(1-FC_{woody})})(1-FC_{woody})\cdot e^{-\gamma\cdot FC_{woody}}]\cdot \frac{g_i}{\sum_{k=1}^{n_{est,woody}} g_k}\cdot(1-mortality)$$

Scheme in LPJ / CLM-DGVM

Mortality of seedling

competition of est. among PFTs

$$g_i = g_{i0}[\varepsilon_0 + (1-\varepsilon_0)FC_i^{\sigma}]$$

- Est. potential
- Background est. rate
- Fractional coverage

$$mort_i = e^{-(\alpha\cdot mort_{greff,i}+\beta\cdot mort_{heat,i})}$$

- Background mortality
- Mortality due to heat stress

•Light competition rank: trees, shrubs, and grasses

Zeng et al., 2013, in press

Turnover

$$\Delta C_{turn} = C_{leaf} f_{leaf} + C_{sapwood} f_{sapwood} + C_{root} f_{root}$$

where C_{leaf}, $C_{sapwood}$, and C_{root} are leaf, sapwood, and root carbon

: f_{leaf}, $f_{sapwood}$, and f_{root} inverse of the pft-dependent tissue longevities

Levis et al., 2004